ISBN: 978-981-94-1156-6
2024 the 14th International Workshop on Computer Science and Engineering (WCSE 2024)
doi: 10.18178/wcse.2024.06.024

A Sectorization Method for Terminal Area of Multi-runway Airports Based on Complexity Models

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Abstract. In the case of limited airspace resources, the continuous increase of air traffic flow makes the construction of multi-runway airports popular in china. The current research on terminal area airspace planning is mainly based on methods such as controller workload and graphic segmentation, and only applies to single runway airports, In this paper, a sectorization method is proposed combined with the characteristics of multi-runway airports and the complexity models. It firstly described the constraints of the sectorization model and the objective function to balance the air traffic complexity. Second, the paper uses the growth algorithm to get model the solution and optimization, and then takes the Chicago O'Hare International Airport as an example to verify the rationality of the method.

Keywords: Air traffic Management, growth algorithm, sectorization, multi-runway model

1. Introduction

In 2022, the rapid development of China's civil aviation industry has led to airspace capacity constraints. Since 2019, China initiated the construction of multi-runway intersecting configuration airports, contributing to the development and operation of large airport clusters, making multi-runway airports one of the dominant trends in China's civil aviation industry. However, the terminal area, serving as the transitional airspace connecting airports and airways, often acts as a bottleneck in the entire air traffic control system. In certain multi-runway terminal areas with denser flight traffic, multiple sectors are required for air traffic control. China's airspace reform urgently demands research on the airspace aspects of multi-runway terminal areas, thus prompting this study's focus on this topic.

Research on terminal airspace delineation began quite early. In the early 21st century, Lucio Bianco[1] et al. first proposed a comprehensive system discussing multi-runway and terminal areas. By 2009, Trandac[2], Basu[3]employed algorithms combined with convex polygon balancing for graphical segmentation of sectors. Wei[4], M. Samà[5], Granberg[6] et al. proposed mixed integer linear methods to solve sector division problems. It wasn't until 2020 that Oktal H[7]considered sector complexity and factors affecting controllers' workload, presenting a multi-objective mixed integer mathematical model for sector division. China's research on multi-runway terminal areas has also been evolving. From 2003 to 2005, Han Songchen, Zhang Ming[8-10]proposed Voronoi division for two-dimensional controlled airspace. Since then, Luo Jun, Lv Huanliang[11]and Zhou Yufan[12], have proposed advanced algorithms like particle swarm optimization for terminal area studies. In 2020, Hu Qingyun[14] introduced an optimization method for terminal area sectors based on complex airspace, encompassing complexity analysis and branch and bound principles.The research on terminal area sectors and multi-runway airports have showcased advanced and innovative methodologies. However, some shortcomings persist, such as limited studies that merge the factors of multi-runways and terminal areas, particularly the distinct characteristics of multi-runways that have been seldom addressed.And from the perspective of the solution algorithm, the growth algorithm is commonly used in image segmentation, but its application in civil aviation has only recently emerged.

The organization of this paper is as follows: In Section 2, it firstly analyze the constraints within the sectorization model and defines an objective function aimed at balancing air traffic complexity. In Section 3, it employs the growth algorithm to solve the proposed model. In Section 4, it utilizes the Chicago O'Hare

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International Airport as a case study to validate the effectiveness of the proposed method, and conclusions are presented in Section 5.

2. Sectorization Model of Terminal Area Airspace

2.1. Model Constraints

In the process of sectorization, based on general sector division principles, the optimization model for sector division is constrained by several factors:

(1) Uniqueness constraint of sector division

(2) Continuity constraint of sectors

(3) Integrity constraint of sector units being allocated to complete sectors

(4) Minimum flight time constraint for sectors

(5) Safety distance constraint of route intersection points

(6) Constraint on the angle between sector boundaries and traffic flow

(7) Constraints on sector shapes

(8) Constraints on sector structures

In this paper, we utilize mathematical methods to quantify these constraints and apply them in subsequent models.

2.2. Constructions of Terminal Complexity Model

In addition to the constraints of sectorization, we introduce the concept of airspace sector complexity. We analyze the influencing factors on airspace sectorization and specifically categorize the influencing factors of airspace sector complexity into two major classes: internal sector structure and operational conditions within the sector. The internal sector factors encompass sector area, route conditions, intersection status, and the number of runways. Operational conditions within the sector include traffic flow density, aircraft type mix, and aircraft status mix. These seven key influencing factors interact with each other, determining the complexity and difficulty of air traffic.

Therefore, the terminal area airspace sector complexity model obtained in this paper is as follows:

$$TC_i = \sum_{m=1}^{7} \omega_m^i \cdot TCF_m^i \tag{1}$$

TC_i： Complexity of sector i

ω_m^i： Influence coefficient of the m-th influence factor（m=1，2⋯,7）, obtained by analyzing the questionnaire of the controllers

TCF_m^i： The influence factor of the m complexity

2.3. Multi-runway Terminal Area Airspace Sectorization Model

(1) Selection of Key Route Points

Initially, navigation facilities, route intersection points, boundary points, and mandatory reporting points within the terminal area chart are selected as key points to generate an initial Voronoi partitioning diagram for the airspace. This initial partitioning aids in establishing the fundamental division of the terminal airspace, facilitating the subsequent methods and model establishment.

(2) Selection of Peak Periods

As a critical aspect ensuring the safety of air traffic, air traffic controllers face intense work pressures. The workload for controllers varies during different time periods, implying that at certain moments, they encounter more intense and busy workloads. Therefore, this paper chooses peak traffic flow periods for sector division, maximizing the utilization of existing resources to ensure a more comprehensive and scientifically derived division result.

(3) Sectorization Model

To optimize terminal area sectors and facilitate the computerized processing of the researched problem, this paper makes the following assumptions:

1) The operational capacity of air routes and route points within the terminal area meets the demands of daily flight volumes.

2) It does not consider situations like diversions, alternate landings, or route changes due to adverse weather conditions.

The optimization of sectorization in this paper primarily aims to balance the complexity of air traffic between sectors. The objective function for optimizing sectorization is as follows:

$$Z = min\left(\sum_{j}^{m}\left|C_j - \overline{C}\right|\right) \tag{2}$$

C_j: a sector in which a number of finite units are combined to form a sector j

N_j: the air traffic complexity of sector j, $C_j = \sum_{i \in N_j} TC_i$

$\overline{C}$: the average traffic complexity of airspace sector, $\overline{C} = \frac{1}{m}\sum_{j=1}^{m} C_j$

The constraints on sector division are as described above, but these constraints do not consider the characteristics of multi-runway airports, and a sector cannot contain too many runways. Therefore, the following constraints need to be added on the basis of the above:

$$\sum_{r=1}^{R} x_{ir} \leq 2R \tag{3}$$

$$x_{ir} = 0,1,2 \tag{4}$$

R: Number of runways at the airport.

3. Model Solution

This paper introduces a novel airspace partitioning growth algorithm based on the optimization principles of airspace sectoring. The aim is to optimize different combinations of sector units by reducing spatial complexity. This method involves selecting S basic sector units and computing the airspace complexity for each unit. Among all sector units, the one with the minimum spatial complexity is chosen for growth. It is then merged with the neighboring sector unit that has the lowest complexity value, resulting in a new complexity value, representing the difference between the sectors at this point. Subsequently, the difference in airspace complexity values between S sector units is determined. This difference is employed as pheromone information in the growth algorithm to compute and derive the optimal combination method which is the global optimum solution.

The pseudo code of the growth algorithm in Matlab is as follows:

```
function globalOptimalSolution = airspacePartitioningGrowth(S, initialComplexities)
    complexities = initialComplexities;
    for i = 1:S
        minComplexityIndex = findMinComplexity(complexities);
        grownUnit = growSectorUnit(minComplexityIndex);
        mergedUnit = mergeWithLowestComplexity(grownUnit);
        diffComplexity = calculateDifference(complexities, mergedUnit);
        applyPheromone(diffComplexity);
    end
    globalOptimalSolution = computeGlobalOptimal();
end
```

Fig. 1: The pseudo code in Matlab of growth algorithm.

4. Experimental Verification

This paper selects the peak flow hours of Chicago O'Hare Airport from 10:00 to 11:00 local time on August 15, 2019, and calculates the corresponding complexity values by collecting relevant data for each sector unit. Figure 2 shows the statistical data for some sector units.

Firstly, divide the sector units into three sectors, as shown in the following figure 2. The black solid line represents the boundary of the controlled airspace, the blue dashed line represents the sector division line, and the red short line represents the runway distribution.

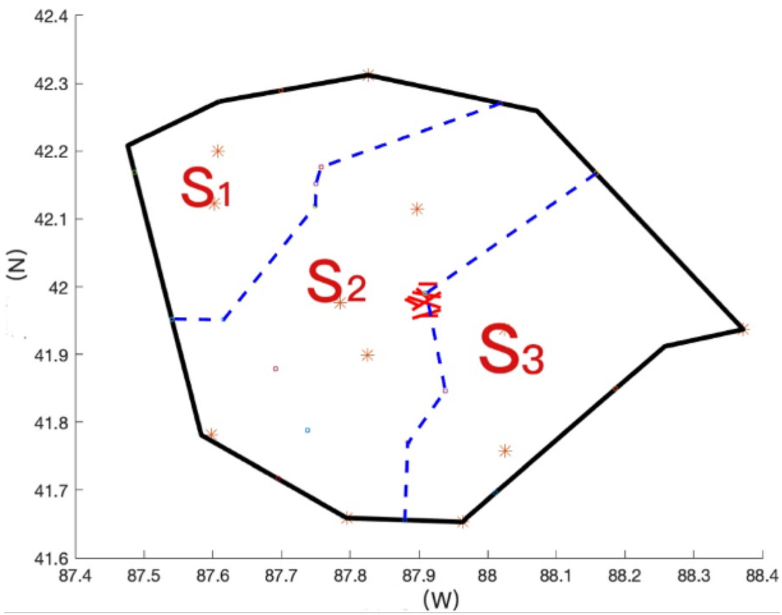

Fig. 2: Initial sector division result

By using the complexity model mentioned earlier, the complexity values of each sector unit can be obtained, and then the growth algorithm can be used to complete the combination optimization of sector units. The optimized partitioning method can be obtained as shown in the figure 3：

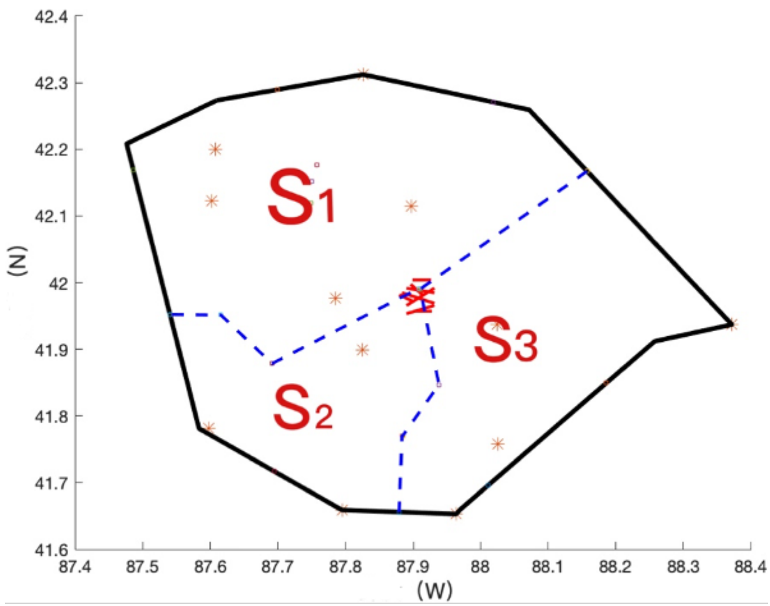

Fig. 3: Sector division result after optimization

From the perspective of balancing the complexity between sectors, the partition results obtained in this article are relatively satisfactory. As shown in Table 1, the complexity value of sector S2 has significantly decreased. Research in relevant articles shows a positive correlation between the complexity value within the sector and the workload of controllers, indicating that the workload of controllers in sector S2 has also decreased. Therefore, from the perspective of controller workload, the proposed sector partition scheme in this article meets the requirements of sector partitioning.

Table 1: Complexity comparison before and after sector optimization

Before optimization	Value of complexity	After optimization	Value of complexity
S1	31.3	S1	53.3
S2	71.7	S2	49.7
S3	47.8	S3	47.8

From the perspective of the runway, combined with the route conditions in the terminal area, some routes corresponding to runways 10C and 10L have been divided from sector S2 to sector S1, which to some extent also slows down the workload of sector S2.

5. Conclusion

This paper considers the constraints on the number of runways in multi-runway airports and establishes a division model based on the balance of complexity in the airspace sector. In the experimental verification, we used flow data from 10:00-11:00 local time on August 15, 2019 at Chicago O'Hare International Airport in the United States to generate an initial sector division and optimized result graph for its controlled airspace, achieving the expected results.

Overall,this paper implements terminal area airspace sectorization for multi-runway airports, filling a certain gap in the research field of terminal area division and having reference significance.

6. References

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