A framework for the optimization of terminal airspace operations in Multi-Airport Systems

多机场系统终端空域运行优化框架

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摘要

Major cities like London, New York, and Tokyo are served by several airports, effectively creating a Multi-Airport System (MAS), or Metroplex. The operations of individual Metro-plex airports are highly interdependent, rendering their efficient management rather difficult. This paper proposes a framework for the design of dynamic arrival and departure routes in MAS Terminal Maneuvering Areas, which fundamentally changes the operation in MAS airspaces for much improved efficiency when compared to the current situation. The framework consists of three components. The first presents a new procedure for characterizing dynamic arrival and departure routes based on the spatio-temporal distributions of flights.

The second component is a novel Analytic Hierarchy Process (AHP) model for the prioritization of the dynamic routes, which takes into account a set of quantitative and qualitative attributes important for MAS operations. The third component is a priority-based method for the positioning of terminal waypoints as well as the design of three-dimensional, conflict-free terminal routes. Such a method accounts for the AHP-derived priorities while satisfying the minimal separation and aircraft maneuverability constraints. The developed framework is applied to a case study of the New York Metroplex, using aircraft trajectories during a heavy traffic period on typical day of operation in the New York Terminal Control Area in November 2011. The proposed framework is quantitatively assessed using the AirTOp fast-time simulation model. The results suggest significant improvements of the new design over the existing one, as measured by several key performance indicators such as travel distance, travel time, fuel burn, and controller workload. The operational feasibility of the framework is further validated qualitatively by subject matter experts from the Port Authority of New York and New Jersey, the operator of the New York Metroplex.

伦敦、纽约和东京等大城市由多个机场提供服务，有效地形成了一个多机场系统 (MAS) 或航空枢纽。各个航空枢纽的运作高度相互依赖，使得它们的高效管理变得相当困难。本文提出了一个设计 MAS 终端机动区域动态进离港航线的框架，该框架从根本上改变了 MAS 空域的运作方式，与当前情况相比，效率大大提高。该框架包括三个组成部分。第一部分提出了一种基于航班时空分布特征来表征动态进离港航线的新方法。第二部分是一个新颖的分析层次过程 (AHP) 模型，用于动态航线的优先级排序，该模型考虑了对于 MAS 运作重要的一系列定量和定性属性。第三部分是一种基于优先级的终端航点定位方法以及三维无冲突终端航线的设计。该方法在满足最小间隔和飞机机动性约束的同时，考虑了由 AHP 得出的优先级。开发的框架应用于纽约航空枢纽的一个案例研究，使用了 2011 年 11 月纽约终端控制区典型运营日高峰时段的飞机轨迹。提出的框架使用 AirTOp 快速时间模拟模型进行了定量评估。结果表明，新设计在旅行距离、旅行时间、燃油消耗和管制员工作量等多个关键性能指标上都有显著改进。该框架的运营可行性还得到了纽约和新泽西港务局——纽约航空枢纽运营商的领域专家的定性验证。

1. Introduction

1. 引言

The continuous increase in air travel demand coupled with rapid urban growth during the past century has resulted in the emergence of secondary airports in the proximity of large metropolitan areas (Sidiropoulos et al., 2015). These are in addition to the primary airport serving a given area, and together this gives rise to a Multi-Airport System (MAS) or ”Metroplex” (e.g. London, New York, Tokyo). Due to the spatial proximity of the Metroplex airports, their operations are interdependent and complex, rendering their efficient management a difficult challenge (Lall, 2018). In the absence of an effective centralized coordination of the operations, the prevailing practice in such systems is for Air Traffic Controllers (ATCos) to allocate traffic in an ad-hoc manner based on their experience. This results in a sub-optimal utilization of the potential capacity of the system (Clarke et al., 2010).

在过去的一个世纪中，航空旅行需求的持续增长和城市的快速扩张导致了大型都会区附近次级机场的出现 (Sidiropoulos 等人，2015 年)。这些机场除了为特定区域提供服务的主要机场外，共同构成了多机场系统 (MAS) 或“机场群”(例如伦敦、纽约、东京)。由于机场群内机场的空间接近，它们的运营是相互依赖且复杂的，使得它们的高效管理成为一个难题 (Lall，2018 年)。在缺乏有效集中协调运营的情况下，这类系统中普遍的做法是空中交通管制员 (ATCos) 根据他们的经验以临时方式分配交通。这导致系统潜在容量的次优利用 (Clarke 等人，2010 年)。

There have been a few attempts to optimize the operation of MAS Terminal Maneuvering Area (TMA), primarily through airspace redesign consultations (Los Angeles World Airports, 2014; NATS, 2013; U.S. Government Accountability Office (GAO), 2008). However, such attempts often rely on ad-hoc measures tailored for specific airport systems; for example, Visual Flight Rules (VFR) corridors have been allocated in both the New York and Los Angeles basin Metroplexes. Unsurprisingly, while such measures may result in locally improved solutions for an individual airport, they are often sub-optimal for the system of

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airports, and pose numerous difficulties in their widespread deployment due to a lack of transferability. In view of this, a number of generic attempts have been made to improve Metroplex operations, including: improved aircraft scheduling, optimized capacity trade-offs and optimized infrastructure planning (McClain, 2013; Clarke et al., 2012; Atkins et al., 2011; Donaldson and Hansman, 2011; Ramanujam and Balakrishnan, 2009; de Neufville, 1995; Hansen, 1995; Hansen and Weidner, 1995; Hansen and Du, 1993). However, all these approaches are limited by the current terminal airspace structure, i.e. its geometry, which is given a priori. In contrast, it is our contention in this paper that the existing static airspace structures may be the main impediment for improving Metroplex operations. We demonstrate this by proposing a novel framework for the new design and planning of terminal airspace in the MAS, based on the dynamic airspace configuration (DAC) concept (Kopardekar et al., 2007), together with the improved design of conflict-free arrival and departure routes in order to increase operational efficiency in terms of the travel distance, travel time, fuel burnt, controller workload and cost.

对优化大规模空中交通系统 (MAS) 终端机动区 (TMA) 的运营已进行了几次尝试，主要是通过空域重新设计咨询 (洛杉矶世界机场，2014 年；NATS，2013 年；美国审计总署 (GAO)，2008 年)。然而，这些尝试通常依赖于针对特定机场系统量身定制的权宜措施；例如，在纽约和洛杉矶盆地的 Metroplexes 中分配了目视飞行规则 (VFR) 走廊。不出所料，虽然这些措施可能会为单个机场带来局部改进的解决方案，但往往对机场系统整体而言并不最优，并且由于缺乏可转移性，在广泛应用时存在许多困难。鉴于这一点，已经进行了一些通用的尝试来改善 Metroplex 运营，包括: 改进飞机调度、优化容量权衡和优化基础设施规划 (McClain，2013 年；Clarke 等人，2012 年；Atkins 等人，2011 年；Donaldson 和 Hansman，2011 年；Ramanujam 和 Balakrishnan，2009 年；de Neufville，1995 年；Hansen，1995 年；Hansen 和 Weidner，1995 年；Hansen 和 Du，1993 年)。然而，所有这些方法都受限于当前的终端空域结构，即其几何形状是预先给定的。相比之下，本文的观点是，现有的静态空域结构可能是改善 Metroplex 运营的主要障碍。我们通过提出一种基于动态空域配置 (DAC) 概念 (Kopardekar 等人，2007 年) 的 MAS 终端空域新设计与规划框架，以及改进无冲突进近和离港路线的设计，以增加运营效率，在旅行距离、旅行时间、燃油消耗、管制员工作量和成本方面进行了证明。

This framework takes both a systematic and holistic approach for a paradigm-shifting design of MAS terminal airspaces, through the seamless integration of a:

该框架采用系统和整体的方法，对 MAS 终端空域的设计进行范式转变，通过以下方面的无缝集成:

- demand characterization method that identifies major traffic flow patterns during the operational horizon(24h), and derives dynamic routes accordingly (see Section 3);

- 需求特征化方法，用于识别操作时间范围内 (24 小时) 的主要交通流模式，并据此派生动态航线 (参见第 3 节)；

- route prioritization framework that enables the decision maker to influence the design based on a set of demand characteristics essential for MAS operations (see Section 4.2); and

- 航线优先级框架，使决策者能够基于对 MAS 运行至关重要的一组需求特征来影响设计 (参见第 4.2 节)；以及

- 3-D routing problem for constructing the airspace structures (arrival and departure routes) in accordance to the dynamic routes (see Section 4.4).

- 构建空域结构 (到达和出发航线) 的三维航线问题，以符合动态航线 (参见第 4.4 节)。

This framework embraces a novel Concept of Operations (CONOPs), namely the dynamic route concept, which shifts from the traditional ad-hoc, First-Come-First-Serve (FCFS) service policy that handles aircraft individually, towards a strategic service policy based on the systematic assignment of aircraft to a set of dynamic routes. A dynamic routes defined to be a group of flights that share similar spatial and temporal characteristics. In addition, we let each dynamic route be associated with exactly one MAS airport and consist of either arrival or departure flights to/from that airport.

该框架采用了新颖的作战概念 (CONOPs)，即动态航线概念，它从传统的临时性、先来先服务 (FCFS) 服务策略，转向基于系统地将飞机分配到一组动态航线的战略服务策略。动态航线定义为具有相似空间和时间特征的航班群。此外，我们让每条动态航线仅与一个 MAS 机场相关联，并包含到达或离开该机场的航班。

The proposed CONOPs recognize significant traffic flow patterns as they evolve in both space and time; and the designed routes are meant to dynamically accommodate such demand patterns. The dynamic route service policy allows the MAS operations to achieve a higher level of efficiency, which is demonstrated in this paper by the use of fast-time simulation modeling (see Section 6). Furthermore, it enhances the First-Come-First-Serve (FCFS) principle, which can be applied to existing flights already assigned to specific dynamic routes, thus promoting equity. In order to do this either, the air traffic controllers can either handle the established traffic on a FCFS basis, or schedule flights along each dynamic route in order to further optimize the operations. The dynamic route service policy can be applied to operations at either the strategic (a few days prior to flight) or pre-tactical (up to 3 h prior to flight) levels. A hallmark of the research presented in this paper is the generic nature of the proposed methodology and its compatibility with subsequent, case-specific designs. The complete framework for developing and assessing the proposed concept is summarized in Fig. 1.

提出的 CONOPs 识别在空间和时间上演变的显著交通流量模式；设计的航线旨在动态适应这种需求模式。动态路由服务策略允许 MAS 操作达到更高的效率水平，本文通过使用快速时间仿真模型 (参见第 6 节) 来证明这一点。此外，它增强了先来先服务 (FCFS) 原则，该原则可以应用于已经分配到特定动态航线的现有航班，从而促进公平。为了做到这一点，空中交通管制员可以基于 FCFS 原则处理已建立的交通，或者沿每个动态航线安排航班，以进一步优化操作。动态路由服务策略可以应用于战略 (飞行前几天) 或预先战术 (飞行前 3 h) 级别的操作。本文呈现的研究的一个特点是其提出的方法论的通用性和与后续特定案例设计的兼容性。用于开发和评估所提出概念的完整框架在图 1 中总结。

Previous research typically overlooks the operational feasibility of the proposed solutions for a Metroplex. It is worth noting that the focus of the previous research is either on arrival or departure operations in isolation, or on the operation of a subset of the Metroplex airports irrespective of the others. Isolating a subset of operations fails to represent the complexity of the full-scale problem, and thus the feasibility and effectiveness of any proposed solutions may be compromised. This paper bridges this gap through a comprehensive assessment of the proposed framework using fast-time simulation modeling (FTS) (AirTOp soft) of the entire New York MAS, comprising of the airports of John F. Kennedy (JFK), LaGuardia (LGA), Newark Liberty International Airport (EWR) and Teterboro (TEB), arguably among the most complex Metroplex systems in the world in terms of the number and proximity of the airports, as well as its current airspace design. In addition, qualitative confirmation of the operational feasibility of the proposed framework is obtained through structured interviews with Subject Matter Experts (SMEs) from the Port Authority of New York and New Jersey (PANYNJ) and the Federal Aviation Administration (FAA). [1] FTS is a useful technique for rapidly evaluating the feasibility and efficiency of airspace design scenarios based on realistic and accurate inputs. In this paper, the current operational features in the New York MAS are accurately replicated in the FTS using the Performance Data Analysis and Reporting System (PDARS) data provided by the PANYNJ. The simulation results of the proposed design indicate a substantial improvement over the current MAS operations,

以往的研究通常忽视了所提出解决方案在大型机场系统 (Metroplex) 中的运营可行性。值得注意的是，以往研究的重点要么是单独考虑到达或出发操作，要么是研究大型机场系统中某个机场子集的运营，而忽略了其他机场。将运营的某个子集独立出来，无法体现全规模问题的复杂性，因此可能会影响所提出解决方案的可行性和有效性。本文通过使用快速时间模拟模型 (FTS)(AirTOp 软件) 对整个纽约大型机场系统进行综合评估，弥补了这一空白。纽约大型机场系统包括肯尼迪机场 (JFK)、拉瓜迪亚机场 (LGA)、纽瓦克自由国际机场 (EWR) 和特特波罗机场 (TEB)，在机场数量、机场之间的接近程度以及当前的空域设计方面，可以说是世界上最为复杂的大型机场系统之一。此外，通过与纽约和新泽西港务局 (PANYNJ) 以及联邦航空管理局 (FAA) 的主题专家 (SMEs) 进行结构性访谈，获得了所提出框架运营可行性的定性确认。[1] FTS 是一种有用的技术，可以基于现实和准确的输入快速评估空域设计方案的可行性和效率。在本文中，使用 PANYNJ 提供的性能数据分析与报告系统 (PDARS) 数据，在 FTS 中准确地复制了纽约大型机场系统当前的操作特征。所提出设计的模拟结果表明，与当前的机场系统运营相比，在多个关键性能指标 (KPIs) 上，包括总飞行距离、旅行时间、燃油消耗和空中交通管制员的工作负荷等方面均有显著改进 (具体细节见第 6 节)。

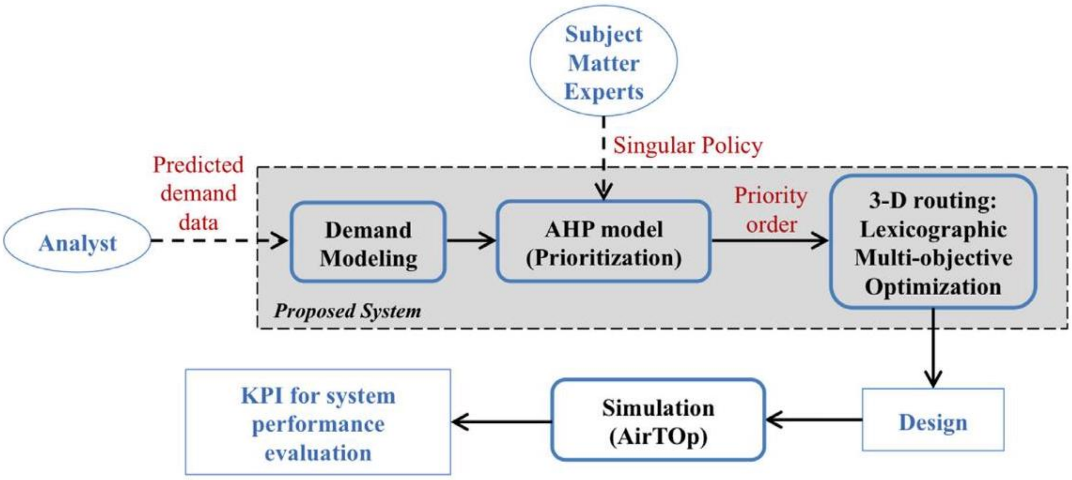


Fig. 1. Framework for developing and assessing the proposed concept of operations.
图 1. 开发和评估所提出操作概念框架。

as measured by several Key Performance Indicators (KPIs) including the total distance travelled, travel time, fuel burnt and air traffic controller workload (see Section 6 for details). The main contributions made by this paper are elaborated as follows.

如多个关键性能指标 (KPIs) 所衡量，包括总飞行距离、旅行时间、燃油消耗和空中交通管制员工作负荷 (具体细节见第 6 节)。本文的主要贡献如下所述。

i. Dynamic route design. Based on the dynamic route concept, we provide a novel methodology for terminal airspace design in high-density terminal airspace that accounts for dynamic demand patterns as they evolve temporally and spatially. Our approach is novel also because it focuses on separation of flights at the route level (individual flights are assigned to specific optimal routes) rather than on a flight-by-flight basis. The latter has been the focus of most studies (e.g. Nikoleris and Erzberger, 2014) and is not a viable solution for high-density airspace in the authors' opinion. Moreover, the existing standards and regulations regarding terminal airspace design (Eurocontrol, 2013) fail to provide a design methodology specific to Metroplex systems or high-density terminal operations. The dynamic route concept aims directly to tackle this and, through this paper, outlines a complete and detailed framework for the design of such airspaces. Finally, while Standard Instrument Departure Routes (SIDs) and Standard Instrument Arrival Routes (STARs) in current operations are typically ignored due to their inefficient design and non-responsiveness to growing demand, to be replaced by vectoring (Interview, 2015), the dynamic route concept allows terminal airspace structures to be utilized in fundamentally new ways.

i. 动态航线设计。基于动态航线概念，我们为高密度终端空域提供了一种新颖的设计方法，该方法考虑了随着时间和空间演变的动态需求模式。我们的方法之所以新颖，还因为它专注于在航线级别上分离航班 (将单个航班分配到特定的最优航线)，而不是基于逐个航班的方式。后者一直是大多数研究 (例如 Nikoleris 和 Erzberger，2014) 的重点，但在作者看来，这不是高密度空域的可行解决方案。此外，现有关于终端空域设计的标准和规定 (Eurocontrol，2013) 未能提供针对 Metroplex 系统或高密度终端运行的具体设计方法。动态航线概念直接旨在解决这一问题，并通过本文概述了一个完整且详细的框架，用于设计此类空域。最后，尽管在当前操作中，标准仪表离场航线 (SIDs) 和标准仪表进场航线 (STARs) 通常由于设计效率低下和对日益增长的需求反应不敏感而被忽略，取而代之的是向量引导 (访谈，2015)，但动态航线概念允许以全新的方式利用终端空域结构。

ii. Multi-Objective Optimization (MOO). The 3-D routing of all the dynamic routes is solved by a Lexicographic Multi-Objective Optimization (LMOO) method. This method is novel as it is the first attempt to utilize a semi-qualitative method (i.e. the AHP) in order to analyze, decompose and synthesize the numerous criteria involved in real-world decision making that pertain to terminal airspace management. The resulting routing algorithm, by virtue of the AHP, is the first to provide feasible, efficient and up-to-date routes that can be used in real operations. To the best of our knowledge, this is the most comprehensive use of the AHP method applied to air traffic management (ATM) routing to date. Moreover, the AHP reduces a computationally intractable MOO problem into a sequence of routing problems that are much easier to solve, while accounting for all the operational considerations.

ii. 多目标优化 (MOO)。所有动态路由的三维路由问题通过字典序多目标优化 (LMOO) 方法解决。这种方法是新颖的，因为它是首次尝试利用半定性的方法 (即层次分析法 AHP) 来分析、分解和综合实际决策中涉及到的众多标准，这些标准与终端空域管理相关。得益于 AHP，生成的路由算法首次提供了可

行、高效且实时更新的路由，可用于实际操作。据我们所知，这是迄今为止将 AHP 方法应用于空中交通管理 (ATM) 路由的最全面的应用。此外，AHP 将一个计算上不可解的多目标优化问题简化为一连串更容易解决的路由问题，同时考虑了所有的运营因素。

iii. Real-world validation. The effectiveness and real-world relevance of our methodology is demonstrated by the user of fast-time simulation (FTS) as an external method of validation. Real-world operations data was collected and processed to provide a realistic, quantifiable assessment of terminal airspace design for a typical operational period in the NY MAS. Comparison with the current situation proves our design to be superior by a significant margin, as measured by several KPIs. We also conduct a qualitative validation of our design, by inviting SMEs to examine the proposed routing structures as well as the feasibility of the entire design. Last but not least, our study covers the entire four-airport NY Metroplex, internalizing all the interdependencies among these airports and providing a holistic investigation of the airspace. This is in contrast with previous studies that use internal methods of validation applied only to a subset of the airports, or specific types of operations in isolation.

iii. 实际验证。我们方法的有效性和实际相关性通过使用快速时间模拟 (FTS) 作为外部验证方法得到证明。收集并处理了实际运营数据，以提供一个典型运营周期内在纽约空域系统 (NY MAS) 的终端空域设计的现实、量化的评估。与当前情况的比较证明了我们的设计在几个关键绩效指标 (KPIs) 上有着显著的优越性。我们还通过邀请行业专家 (SMEs) 检查拟议的路由结构以及整个设计的可行性，进行了定性的验证。最后但并非最不重要的是，我们的研究涵盖了整个纽约大都会区四座机场，内部化了这些机场之间的所有相互依赖关系，并对空域进行了整体研究。这与之前的研究形成对比，那些研究仅使用内部验证方法应用于机场的子集，或孤立地针对特定类型的操作。

iv. Generality and transferability. The proposed methods are validated for the NY Metroplex, which is arguably the most complex terminal airspace in the world, in terms of the number of airports, airport proximity and runway geometry, traffic volumes, traffic mix, airspace user mix and the number of saturated airport runways. Our methodologies pertaining to demand characterization, AHP and 3-D routing do not rely on any assumptions that prevent them from being calibrated and applied to other airport systems. Although the framework is initially designed for Metroplex systems, it can be transferred to the cases of single airport systems with minimum modification, thereby providing an advanced method for terminal aircraft routing and airspace management.

iv. 普遍性和迁移性。所提出的方法在纽约大都会区得到了验证，该区域在机场数量、机场间距和跑道几何形状、交通量、交通组合、空域用户组合以及饱和机场跑道数量方面，可以说是世界上最为复杂的终端空域。我们关于需求特征化、层次分析法 (AHP) 和三维路由的方法并不依赖于任何阻止它们校准和应用于其他机场系统的假设。尽管该框架最初是为大都会系统设计的，但只需进行最小修改即可转移到单一机场系统的案例中，从而为终端飞机路由和空域管理提供了先进的方法。

The proposed design is aligned with the Single European Sky Air Traffic Management Research (SESAR) and Next Generation Air Transportation System (NextGen), as it proposes a centralized framework for design, control, and evaluation of the entire MAS, while allowing for variations in the control strategies via the AHP with up-to-date information. It also embraces the concepts of Dynamic Airspace Configuration (DAC), 4-D trajectories, Arrival Manager (AMAN) and Departure Manager (DMAN) systems, due to its dynamic route concept and compatibility with case-specific designs (e.g. see Section 6.3).

所提出的设计与单一欧洲天空空中交通管理研究 (SESAR) 和下一代航空运输系统 (NextGen) 保持一致，因为它提出了一个集中框架，用于设计、控制和评估整个 MAS，同时通过 AHP 允许控制策略的变化，并使用最新信息。它还融入了动态空域配置 (DAC)、4-D 轨迹、到达管理器 (AMAN) 和出发管理器 (DMAN) 系统的概念，因为其动态路由概念与特定案例设计兼容 (例如，参见第 6.3 节)。

The rest of the paper is organized as follows. Section 2 offers some relevant background and literature review. Section 3 elaborates the procedure for route classification, which serves as a preliminary of the 3-D route design. Section 4 presents the detailed route design problem expressed as a terminal fix selection problem and an AHP-based lexicographic multi-objective optimization problem. A real-world case study of the proposed framework is described in Section 5 and the fast-time simulation-based validation is presented in Section 6. Finally, Section 7 provides some concluding remarks and several future research directions.

本文其余部分的组织如下。第 2 节提供了一些相关的背景和文献综述。第 3 节详细阐述了路由分类的过程，这为 3-D 路由设计提供了初步准备。第 4 节提出了详细的路线设计问题，表述为终端固定点选择问题和一个基于 AHP 的词典式多目标优化问题。第 5 节描述了所提出框架的实际案例研究，第 6 节展示了基于快速时间仿真的验证。最后，第 7 节提供了一些结论性评论和几个未来研究方向。

2. Background and literature

2. 背景和文献

Multi-Airport Systems (MAS) are among the most significant regional scaling mechanisms, enabling the air transportation system to adapt and evolve to meet travel demand (Bonnefoy, 2008). The Joint Planning and Development Office (JPDO) provides a simple definition for Metroplex as: "a group of two or more adjacent airports whose arrival and departure operations are highly interdependent" (Atkins et al., 2011). There have been several definitions of MAS in the literature that utilize a variety of characteristics to describe their formation, including spatial proximity of the airports, traffic volumes (FAA, 2014; McClain, 2013; Bonnefoy, 2008; de Neufville and Odoni, 2003), and ownership of the airports (ACI, 2002). Atkins et al. (2011) provide a set of qualitative and quantitative definitions of Metroplex (e.g. observation-based, model-based and simulation-based) to better describe specific Metroplex phenomena. Most recently, Sun et al. (2017) develop a novel temporal metric to define a Multi Airport Region (MAR) based on the travel time required for passengers to commute between airports. The development of new airports (e.g. the future Beijing Daxing International airport serving the JinglinJi megaregion) and the continuous expansion of existing ones in major metropolitan areas (Li and Ryerson, 2017), as well as the increasing occurrence of Metroplex phenomena even in smaller airport systems (Atkins et al., 2011), all underline the significance of MAS as a key component of the modern ATM system.

多机场系统 (MAS) 是最重要的区域扩展机制之一，使得航空运输系统能够适应并演变，以满足旅行需求 (Bonnefoy，2008)。联合规划与发展办公室 (JPDO) 对 Metroplex 给出了一个简单的定义: "由两个或更多相邻机场组成的一组，其到达和出发操作高度相互依赖" (Atkins 等人，2011)。在文献中，关于 MAS 的定义有几种，它们利用各种特征来描述其形成，包括机场的空间邻近性、客流量 (FAA，2014; McClain，2013；Bonnefoy，2008；de Neufville 和 Odoni，2003) 以及机场的所有权 (ACI，2002)。Atkins 等人 (2011) 提供了一套定性和定量的 Metroplex 定义 (例如基于观察、基于模型和基于模拟)，以更好地描述特定的 Metroplex 现象。最近，Sun 等人 (2017) 开发了一种新的时间指标，用于根据乘客在机场之间通勤所需的时间来定义多机场区域 (MAR)。新机场的建设 (例如未来服务于京津冀大区域的北京大兴国际机场) 以及大都市区现有机场的持续扩建 (Li 和 Ryerson，2017)，以及即使在较小的机场系统中也越来越多地出现 Metroplex 现象 (Atkins 等人，2011)，所有这些都凸显了 MAS 作为现代空中交通管理系统 (ATM) 关键组成部分的重要性。

The effective management of the MAS is a key requirement for the relevant stakeholders including the airports, Air Navigation Service Providers (ANSPs), air traffic controllers, and airspace users (especially the airlines). Currently, MAS operations are loosely coordinated (Clarke et al., 2010), resulting in many system inefficiencies that compromise the stakeholders' goals. The lack of an effective Airport Collaborative Decision Making (A-CDM) leads to non-cooperative gaming among MAS airports for the use of airspace resources (Sidiropoulos et al., 2015). The ANSPs are required to provide the necessary structures that ensure efficient services for both airports and airspace users. However, the lack of effective network planning results in stringent operational constraints on the latter. Airlines face the problem of minimizing their operational costs while providing satisfactory services whilst at the same time having to abide by the relevant regulations and other operational constraints. Under such a competitive operational environment, the burden of coordinating air traffic demand in the MAS is placed on the air traffic controllers, who, due to capacity constraints and increased workload, often resort to the vectoring of flights and the extensive use of holding stacks (mainly in Europe and, to a lesser extent, the US where ground-holding programs are typically employed).

有效管理空管系统 (MAS) 是相关利益相关者的关键要求，包括机场、空中导航服务提供商 (ANSPs)、空中交通管制员和空域用户 (尤其是航空公司)。目前，MAS 的运行协调较为松散 (Clarke 等人，2010 年)，导致许多系统效率低下，损害了利益相关者的目标。缺乏有效的机场协同决策 (A-CDM) 导致 MAS 机场之间为使用空域资源而进行非合作博弈 (Sidiropoulos 等人，2015 年)。ANSPs 需要提供必要的结构，以确保为机场和空域用户提供高效服务。然而，缺乏有效的网络规划导致对后者的运营约束变得严格。航空公司面临着在遵守相关法规和其他运营约束的同时，最小化运营成本并提供满意服务的难题。在如此竞争激烈的运营环境中，协调 MAS 中空中交通需求的负担落在空中交通管制员身上，他们由于容量限制和工作量增加，往往求助于航班的向量引导和大面积使用等待航线 (主要在欧洲，而在美国则较少，地面等待程序通常被采用)。

With the aim of improving Metroplex operations, Ren et al. (2009) analyzed four major US Metroplex areas and identified a set of critical issues and operational interdependencies in these airspaces. The authors developed a framework in order to evaluate the impact of each issue based on a qualitative scale. This they complemented with a link-node queuing process model developed for the optimization of arrival flows. Despite the improved performance of the system in terms of delay, the authors' framework failed to provide a generic methodology as it relied on ad-hoc route geometry. Li et al. (2011) extended the previous model to test three different generic Metroplex layouts (tandem, parallel and crossing). For a given layout, they examined the impact of sharing terminal fixes and the system-wide scheduling of operations. Among the several operational scenarios examined, the decoupling of fixes and the temporal coordination between airports were deemed the preferred options in order to improve system efficiency. Atkins et al. (2011) developed a unified model to simultaneously optimize route assignment, sequencing, and scheduling for aircraft operations in a Metroplex. The resulting deterministic Mixed Integer Linear Program (MILP) problem was applied to a two-airport scenario and achieved a 13% increase in aircraft throughput. However, the scope of Atkins et al. (2011) is limited, as the routing method was developed for specific types of route interactions (e.g. two parallel routes) and the model was only implemented for a specific route interdependency between LGA and TEB airports. Moreover, the model stipulated a priori route geometry and assignment, thereby failing to accommodate more general demand patterns.

为了提高大型机场群的运营效率，Ren 等人 (2009 年) 分析了美国四大大型机场群的运行情况，识别了这些空域中的一系列关键问题和运营相互依赖性。作者们构建了一个框架，以评估每个问题基于定性量表的影响。他们通过开发一个链接-节点排队过程模型来补充该框架，该模型用于优化到达流量。尽管在延迟方面系统的性能得到了改善，但作者们的框架未能提供一种通用方法，因为它依赖于特定的路由几何形状。Li 等人 (2011 年) 扩展了之前的模型，以测试三种不同的大型机场群布局 (串联、并行和交叉)。对于给定的布局，他们研究了共享终端修正和全系统调度操作的影响。在考察的多个运营场景中，修正的解耦和机场之间的时间协调被认为是提高系统效率的首选方案。Atkins 等人 (2011 年) 开发了一个统一模型，以同时优化大型机场群中飞机运行的航线分配、排序和调度。得到的确定性混合整数线性规划 (MILP) 问题应用于两个机场的场景，实现了飞机吞吐量 13% 的增长。然而，Atkins 等人 (2011 年) 的研究范围有限，因为路由方法是针对特定类型的航线交互 (例如两条平行航线) 开发的，而且模型仅针对 LGA 和 TEB 机场之间的特定航线相互依赖性进行了实施。此外，模型规定了先验的航线几何形状和分配，因此无法适应更一般的需求模式。

Another body of literature focuses on demand modeling for the analysis of Metroplex operations. Timar et al. (2010) developed a tool for analyzing the current and future traffic demand, which enables the generation and allocation of demand to terminal fixes for different Metroplex terminal airspace configurations. Their tool aims to assess the impact of directional traffic distribution on flight delays for both Atlanta Hartsfield-Jackson International (ATL) and Los Angeles International (LAX) airports. Their results reveal that flight delays are sensitive to fix loading, and that demand distribution has a significant impact on the delays at the fix, airport, and Metroplex levels. To optimize flight schedules, Timar et al. (2011) developed a model of high traffic density Metroplex airspace operations. This model effectively identified the most frequently used arrival and departure procedures and airways using trajectory-based modeling. The model was developed for the southern California Metroplex consisting of Los Angeles International (LAX), Burbank (BUR), Long Beach (LGB), Ontario (ONT), San Diego (SAN), and Santa Ana (SNA). Validation of this model was by simulations, which provided sufficient detail on the current route structure. While models of this type can be used as the basis for route scheduling algorithms, they are constrained by the existent airspace design and ATC actions.

另一部分文献专注于对大型机场运营的需求建模。Timar 等人 (2010 年) 开发了一个分析当前和未来交通需求的工具，该工具能够生成并将需求分配到不同大型机场终端空域配置的终端固定点。他们的工具旨在评估方向性交通分布对亚特兰大哈茨菲尔德-杰克逊国际机场 (ATL) 和洛杉矶国际机场 (LAX) 航班延误的影响。他们的结果显示，航班延误对固定点的负载敏感，需求分布对固定点、机场和大型机场运营级别的延误有重大影响。为了优化航班时刻表，Timar 等人 (2011 年) 开发了一个高交通密度大型机场空域运营的模型。该模型通过基于轨迹的建模有效地识别了最常使用的到达和出发程序以及航路。该模型是为包括洛杉矶国际机场 (LAX)、伯班克 (BUR)、长滩 (LGB)、安大略 (ONT)、圣地亚哥 (SAN) 和圣安娜 (SNA) 在内的南加州大型机场开发的。该模型的验证是通过模拟进行的，提供了关于当前航线结构的充足细节。虽然这类模型可以作为航线调度算法的基础，但它们受限于现有的空域设计和空中交通管制 (ATC) 的行动。

Focusing on the temporal de-confliction of flights as means to improve Metroplex operations, Wieland et al. (2014) formulated an integrated arrival departure and surface scheduling system for Metroplex operations. The platform consisted of a set of optimization algorithms for sequencing, runway assignment and route allocation with the objectives of maximizing throughput, enhancing safety and minimizing the environmental impact. The model was applied to the NY Metroplex (only for JFK and LGA) for a high-traffic day before Thanksgiving. The model successfully reduced departure delays by 22%. However, the exclusion of EWR and TEB from the analysis is a potential drawback as acknowledged by the authors.

专注于航班的时间冲突解决以提高大都市区 (Metroplex) 运营效率，Wieland 等人 (2014 年) 为 Metroplex 运营制定了一个集成的到达和出发以及地面调度系统。该平台包括一组用于排序、跑道分配和航线分配的最优化算法，目标是在最大化吞吐量、提高安全性和最小化环境影响。该模型被应用于纽约

大都市区 (仅限 JFK 和 LGA) 感恩节前的高流量日。该模型成功地将出发延误减少了 22%。然而，正如作者所承认的，分析中排除了 EWR 和 TEB 可能是一个潜在的缺陷。

The following two Traffic Flow Management (TFM) initiatives for both single-airport and multi-airport terminal airspaces are mentioned here due to their widespread application in terminal airspaces in the U.S. NASA has developed the Traffic Management Advisor (TrMA) [2] (Nedell et al.,1990) and the Precision Departure Release Capability (PDRC) (Engelland et al., 2013) tools, for the scheduling of arrivals and departures, respectively. The primary function of the TrMA is the real-time scheduling of arriving traffic within approximately 200NM from touchdown. The tool is superior to other AMAN systems, as the scheduler is complemented by a graphical user interface and by additional interactive tools that aid the adjustment of schedules. The PDRC, on the other hand, optimizes the departure schedule for take-off times with a high precision. For flights with PDRC, the schedule is automatically communicated to the Air Route Traffic Control Center (ARTCC), which, in turn, calculates the ascent trajectories from the take-off point to the merge point in the overhead flow. With the goal of improving flow efficiency and reducing controller workload, both the TrMA and the PDRC are deployed in several terminal areas in the United States, including Metroplexes.

在此提及以下两个针对单机场和多机场终端空域的流量管理 (TFM) 倡议，因为它们在美国终端空域中得到了广泛应用。NASA 开发了流量管理顾问 (TrMA) [2] (Nedell 等人，1990 年) 和精确出发释放能力 (PDRC)(Engelland 等人，2013 年) 工具，分别用于安排到达和出发。TrMA 的主要功能是在飞机着陆前大约 200NM 的时间内实时安排到达交通。该工具优于其他 AMAN 系统，因为调度器配备了图形用户界面和额外的交互式工具，以帮助调整计划。另一方面，PDRC 优化了起飞时间的出发计划，具有高精度。对于使用 PDRC 的航班，计划会自动传达给空中路线交通管制中心 (ARTCC)，ARTCC 接着计算从起飞点到 overhead flow 合流点的爬升轨迹。为了提高流量效率和减轻管制员的负担，TrMA 和 PDRC 都在美国的几个终端区域部署，包括 Metroplexes。

Given the significance of Metroplex systems for serving air traffic demand in large metropolitan regions (e.g. New York, Los Angeles, San Francisco), the FAA has initiated the Optimization of Airports and Procedures in Metroplex (OAPM) (FAA, 2014) task force for the improvement of operations. OAPM identified 21 sites as Metroplex areas throughout the United States (FAA, 2014) and assigned dedicated study teams to explore the opportunities for improving their operations. However, OAPM has mainly focused on less busy Metroplex systems so far [e.g. Houston Metroplex comprising of one primary and one secondary airport (Bonnefoy, 2008)], implementing ad-hoc measures to improve operations without providing a general model for the holistic terminal airspace design.

鉴于大都市区域 (例如纽约、洛杉矶、旧金山) 的空中交通需求对大型机场系统的重要性，美国联邦航空管理局 (FAA) 启动了大型机场和程序优化 (OAPM) 特别工作组 (FAA，2014)，以改善运营。OAPM 在美国确定了 21 个大型机场区域 (FAA，2014)，并指派专门的研究团队探索改善其运营的机会。然而，到目前为止，OAPM 主要关注较不繁忙的大型机场系统，例如由一个主要机场和一个次要机场组成的休斯顿大型机场系统 (Bonnefoy，2008)，实施临时措施来改善运营，而没有提供一个用于整体终端空域设计的通用模型。

In order to overcome the aforementioned limitations, as stated earlier, this paper proposes a novel concept of operations based on Dynamic Airspace Configuration (DAC) (Kopardekar et al., 2007). While most studies relating to dynamic airspace configuration focus on the en-route phase, i.e. dynamic sector configurations (Sergeeva et al., 2017; Zelinski and Lai, 2011; Bloem and Gupta, 2010; Gianazza, 2010; Klein et al., 2008; Martinez et al., 2007; Delahaye et al., 1998), only a few in the literature have adopted the concept of DAC for terminal area operations. In terminal airspace, the most widely studied DAC concept is the dynamic airspace sectorization, which concerns with the re-configuration of the sector boundaries within the terminal airspace and attempts to increase airspace capacity by re-distributing the workload of the ATCos (Kopardekar et al., 2009). This concept allows the airspace to adapt to the wind conditions that determine the runway configurations. Currently, however, dynamic sectorization is not supported by any decision support tools to assist in the selection of the optimal airspace configuration so as to reflect the projected traffic demand or weather conditions (Kopardekar et al., 2009). Rather, these are done in an ad-hoc manner based on prior experience, and inevitably lead to sub-optimal operations of the system, which affect en-route sectors surrounding the terminal airspace (Kopardekar et al., 2009).

为了克服前述限制，如前所述，本文提出了基于动态空域配置 (DAC)(Kopardekar 等人，2007 年) 的新型操作概念。尽管大多数关于动态空域配置的研究都集中在航路阶段，即动态扇区配置 (Sergeeva 等人，2017 年；Zelinski 和 Lai，2011 年；Bloem 和 Gupta，2010 年；Gianazza，2010 年；Klein 等人，2008 年；Martinez 等人，2007 年；Delahaye 等人，1998 年)，但文献中只有少数研究采用了 DAC 概念用于终端区域操作。在终端空域中，研究最为广泛的 DAC 概念是动态空域扇区划分，它涉及在终端空域内重新配置扇区边界，并试图通过重新分配空中交通管制员 (ATCos) 的工作负担来增加空域容量 (Kopardekar 等人，2009 年)。这个概念允许空域适应决定跑道配置的风力条件。然而，目前动态扇区划

分并没有得到任何决策支持工具的支持，以辅助选择最佳的空域配置，以反映预测的流量需求或天气条件 (Kopardekar 等人，2009 年)。相反，这些操作是基于以往经验以临时方式进行的，并且不可避免地导致系统的次优操作，这影响了终端空域周围的航路扇区 (Kopardekar 等人，2009 年)。

To overcome this limitation, the transition towards a functional type of sectorization is made via the concept of tube design for terminal routes. Kopardekar et al. (2009) suggest that tube design can serve as dedicated conflict-free arrival and departure routes in terminal airspace, providing guidance between the Top Of Descent (TOD)/Top Of Climb (TOC) and the final approach fix/take-off for arrivals and departures, respectively. The configuration of these corridors should be dynamic and reflect the current traffic and weather conditions (e.g. avoidance of adverse weather) (Kopardekar et al., 2009). The conflict-free terminal routes alleviate the need for ATC to provide lateral and vertical separation between aircraft on different routes, and instead enable them to simply monitor and ensure that aircraft stay on their predefined flight path and maintain the required longitudinal separation between aircraft on the same route. This approach can effectively increase airspace capacity by overcoming the limitation imposed by controller workload.

为了克服这一限制，通过终端航路管道设计的概念，实现了向功能型区域划分的过渡。Kopardekar 等人 (2009 年) 建议，管道设计可以作为专门的、无冲突的进近和起飞航路，在终端空域提供从下降点/上升点 (TOD/TOC) 到最终进近定位点/起飞点的引导。这些走廊的配置应该是动态的，并反映当前的交通和天气状况 (例如，避开恶劣天气)(Kopardekar 等人，2009 年)。无冲突的终端航路减轻了空管 (ATC) 在不同航路上的飞机之间提供横向和垂直间隔的需求，相反，它们可以简单地监控并确保飞机保持在预定的飞行路径上，并在同一航路上的飞机之间保持所需的纵向间隔。这种方法可以通过克服由管制员工作负荷带来的限制，有效地提高空域容量。

The importance of DAC in the TMA has been acknowledged by both the NextGen and SESAR programs with the use of strategically de-conflicted trajectories as the preferred and most efficient solution for highly congested areas (Eurocontrol, 2008; Hahn et al., 2007). However, literature on the design of dynamic terminal routes is rather scarce. Chen et al. (2012) and Chen et al. (2013) proposed a model for the optimal routing in single-airport systems by combining the DAC with an extended terminal airspace design, which includes additional airspace, thereby providing flexibility to enable severe weather avoidance. Zhou et al. (2014) proposed a fast-marching method for sequentially designing the 3-D routes, where a metaheuristic method is employed to determine the optimal order by which the routes are designed. However, such a heuristic approach ignores operational considerations and constraints, thereby rendering the approach impractical. Pfeil (2011) developed a model for a single-airport TMA DAC under uncertain weather conditions. In this study, an A* -based routing algorithm for the design of conflict-free 3-D terminal routes was proposed with the objective of minimizing the total distance travelled by all the routes. These routes were solved sequentially for arrivals first and subsequently departures. Despite the promising experimental results, the ad-hoc priority order (arrivals over departures) did not allow for additional operational considerations to be incorporated (e.g. arrival/departure push strategies), which are critical in multi-airport environments.

在 TMA 中，DAC 的重要性已经得到了 NextGen 和 SESAR 计划的双重认可，这两个计划都优先选择战略性的冲突解脱轨迹作为高度拥堵区域的最有效解决方案 (Eurocontrol, 2008; Hahn et al., 2007)。然而，关于动态终端航路设计的文献相当稀少。Chen 等人 (2012) 和 Chen 等人 (2013) 提出了一种结合 DAC 和扩展终端空域设计的单机场系统最优航线模型，该模型包括额外的空域，从而提供了避免恶劣天气的灵活性。Zhou 等人 (2014) 提出了一种快速行进方法，用于顺序设计三维航线，其中采用了一种元启发式方法来确定设计航线的最佳顺序。然而，这种启发式方法忽视了运营考虑和约束，从而使该方法不切实际。Pfeil(2011) 在不确定天气条件下开发了一个单机场 TMA DAC 模型。在本研究中，提出了一种基于 A* 的无冲突三维终端航线设计算法，目标是最小化所有航线行驶的总距离。这些航线首先为到达航班解决，然后为出发航班解决。尽管实验结果令人鼓舞，但临时优先顺序 (到达航班优先于出发航班) 并未允许纳入额外的运营考虑 (例如，到达/出发推送策略)，这在多机场环境中至关重要。

Zou (2010) developed the "Tree-Based Route Planner (TBRP)" to produce flexible routing structures in terminal airspaces. The routing structures are modeled as 2-D weather-avoidance trees between an extended terminal airspace boundary (100- 200NM) and one or more arrival fixes of the current terminal airspace boundary (40-50 NM). The TBRP employs a dynamic programming approach for the generation of the weather-avoidance trees with the objectives of maximizing aircraft throughput and minimizing flow complexity. However, the model does not address the design of the route structure in the current terminal airspace (within the $40-50$NM radius). Choi et al. (2010) developed a heuristic scheduling algorithm

Maneuvering Area (TMA).
操纵区 (TMA)。

to investigate the impact of ad-hoc arrival merge point configurations on arrival scheduling performance for an extended terminal airspace design (up to 200NM). The model considers aircraft trajectory uncertainties under the assumption that they are propagated linearly with respect to the route length. However, Choi et al. (2010) model is developed only for the arrival merge points, and ignored both the departures and the remaining arrival route structures.

邹 (2010) 开发了“基于树的路径规划器 (TBRP)”，以在终端空域中生成灵活的航线结构。航线结构被建模为二维的避开恶劣天气的树，位于扩展的终端空域边界 (100- 200NM) 和当前终端空域边界的一个或多个到达定位点 (40-50 海里) 之间。TBRP 采用动态规划方法生成避开恶劣天气的树，目标是最大化飞机吞吐量和最小化流量复杂性。然而，该模型没有解决当前终端空域 (在 40 – 50NM 半径内) 的航线结构设计问题。Choi 等人 (2010) 开发了一种启发式调度算法，以研究临时到达合并点配置对扩展终端空域设计 (高达 200NM) 的到达调度性能的影响。该模型考虑了飞机轨迹的不确定性，假设它们与航线长度成线性传播。然而，Choi 等人 (2010) 的模型仅针对到达合并点开发，忽略了出发和剩余到达航线结构。

In the Metroplex environment, improved management of arrival flows through dedicated terminal fixes and the splitting of arrival flows was observed after a test at the southwest boundary of the New York TRACON (Hahn et al., 2007). The creation of the dedicated ”DYLIN” EWR arrival route combined with relocating area navigation (RNAV)-capable satellite airport traffic to the published JAIKE arrival resulted in reduced controller workload. Dedicated de-conflicted terminal fixes, which can be considered a precursor to the conflict-free routes, are expected to be widely adopted in the NAS in order to handle the future increase of air traffic demand (Hahn et al., 2007).

在 Metroplex 环境中，通过对专用终端定位点的到达流进行改进管理，以及对到达流的分流，在纽约 TRACON 西南边界的测试后观察到了效果 (Hahn 等人，2007)。创建专用的“DYLIN” EWR 到达航线，并结合将能够进行区域导航 (RNAV) 的卫星机场流量转移到公布的 JAIKE 到达航线，降低了管制员的 workload。专用的无冲突终端定位点，可以被视为无冲突航线的先导，预计将在 NAS 中广泛采用，以应对未来航空交通需求的增加 (Hahn 等人，2007)。

Studies concerned with the inevitable evolution of terminal airspace design to meet future air traffic demand suggest the concept of DAC as an adequate solution (FAA, 2013; Kopardekar et al., 2009; Eurocontrol, 2008; Hahn et al., 2007). In particular, Kopardekar et al. (2009) envisaged the future design of super-density Metroplex terminal airspaces enabled by advanced decision support tools considering the dynamic changes in air traffic flows. Kopardekar et al. (2009) and the FAA (2013) recommended that such a system should be supported by efficient RNAV routes, the provision of merge/diverge operations, extended terminal area airspace, expanded use of the 3 NM horizontal separation and the dynamic reconfiguration of sector boundaries.

研究关注终端空域设计不可避免的演变以满足未来航空交通需求，提出 DAC 概念作为一种充分解决方案 (FAA，2013；Kopardekar 等人，2009；Eurocontrol，2008；Hahn 等人，2007)。特别是，Kopardekar 等人 (2009) 设想了通过先进决策支持工具考虑到空中交通流的动态变化，未来设计的超密度 Metroplex 终端空域。Kopardekar 等人 (2009) 和 FAA(2013) 建议，这样的系统应该由高效的 RNAV 航线、合并/分离操作的提供、扩展的终端区域空域、3 海里水平间隔的扩大使用以及扇区边界的动态重构支持。

This paper is significant in that it proposes a new framework for addressing the inefficiencies of Metroplex operations, by switching from the existent static route structure to the dynamic route service policy. To embrace such a concept, appropriate technical approaches have been introduced and implemented in every phase of the TMA design problem, including demand characterization, dynamic route formulation and prioritization, as well as 3-D routing within the TMA.

本文的重要性在于，它提出了一个新的框架来解决 Metroplex 运营的低效率问题，通过从现有的静态路线结构转变为动态路线服务政策。为了接纳这样的概念，适当的技术方法已经在 TMA 设计问题的每个阶段引入并实施，包括需求特征化、动态路线的制定和优先级划分，以及在 TMA 内的三维路由。

3. Demand characterization: spatio-temporal clustering

3. 需求特征化: 时空聚类

A prerequisite for the application of a DAC solution is the accurate depiction of the traffic demand patterns both in space and time. In order to achieve this, the use of adequate and appropriate data is imperative. The data can be drawn from the latest Shared Business Trajectories (SBTs) and distributed via an advanced system [e.g. the Enhanced Traffic Management System (ETMS), Time Based Flow Management (TBFM) in the US]. Airlines use internal optimization systems to calculate the optimal routes of their flights in terms of the fuel consumption, cost and travelled distance (time). However, such optimization problems are constrained by numerous important factors associated with trajectory planning, such as airspace charges, punctuality, weather conditions, airspace configuration and route availability (Saturn project, 2015). The uncertainties associated with these factors can cause significant variability in the air traffic flows of the MAS and they contribute to the consensus regarding the inadequacy of current static airspace structures in serving dynamic air traffic demand. The International Civil Aviation Organization (ICAO) has taken a number of initiatives in an attempt to tackle this issue by revising the current static flight planning procedures (protocols) to provide more flexibility to the airspace users, while at the same time ensuring transparency to the other stakeholders (ICAO, 2012).

应用 DAC 解决方案的前提是对交通需求模式在空间和时间上的准确描述。为了达到这一目标，使用充足且适当的数据是至关重要的。这些数据可以来自最新的共享商业轨迹 (SBTs)，并通过先进的系统分发，例如通过增强交通管理系统 (ETMS)、基于时间的流量管理 (TBFM) 在美国的使用。航空公司使用内部优化系统计算其航班的最佳航线，以降低燃油消耗、成本和飞行距离 (时间)。然而，这类优化问题受到与轨迹规划相关的许多重要因素的制约，例如空域收费、准点率、天气条件、空域配置和航线可用性 (Saturn 项目，2015 年)。这些因素带来的不确定性可能导致 MAS 空中交通流的显著变化，它们也促使人们普遍认为当前静态的空域结构无法满足动态的空中交通需求。国际民用航空组织 (ICAO) 已经采取了一系列措施，试图通过修订当前的静态航班规划程序 (协议) 来解决这一问题，为空域用户提供更大的灵活性，同时确保其他利益相关者的透明度 (ICAO，2012 年)。

Fig. 2 illustrates the directional distribution of arrival and departure flights in a few sampled time periods during a 24-h horizon in the New York Metroplex TMA (Nov 2011). Here, the TMA is modeled as a cylinder with a radius of 150 km and height of 7 km centered at the centroid of the four NY airports. The Y-axis in the figure indicates the direction ($0° - 360°$) at which the flights intercept the TMA boundary, and the X-axis indicates the time of entry/exit. The high concentration of flights observed at certain angles is indicative of the location of arrival or departure fixes. To derive useful information about significant traffic flow patterns and obtain the dynamic routes, a spatio-temporal clustering algorithm (Sidiropoulos et al., 2017) is used as described below.

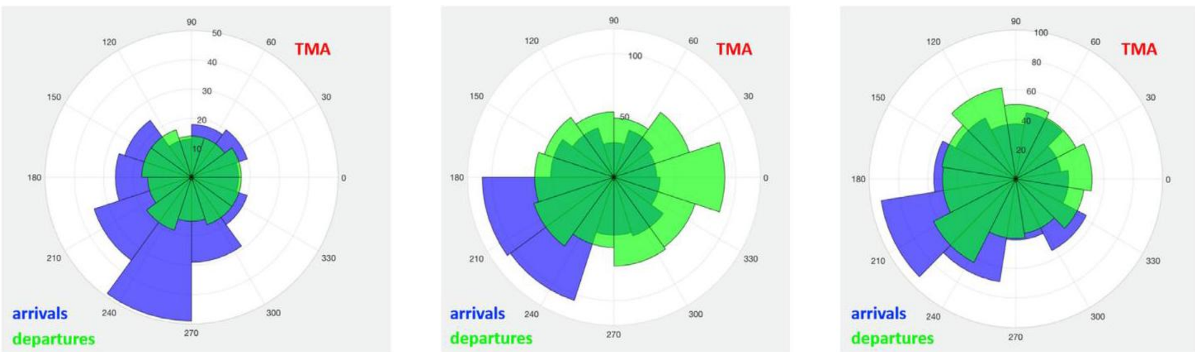
图 2 描述了在纽约大都会终端区管理局 (TMA) 内，在 24 小时范围内的几个采样时间段内到达和出发航班的方位分布。在此，TMA 被建模为一个以四个纽约机场质心为中心，半径为 150 km 高度为 7 km 的圆柱体。图中的 Y 轴表示航班截击 TMA 边界的方向 ($0° - 360°$) ，X 轴表示进入/离开的时间。在特定角度观察到的大量航班集中表明了到达或出发定位点的位置。为了推导有关重要交通流模式的有用信息并获取动态路线，使用了一种时空聚类算法 (Sidiropoulos et al.，2017) 如下所述。

3.1. Temporal clustering

3.1 时空聚类

In order to detect the point in time when there is a significant change in the temporal distribution of flights in the terminal area, the following procedure is followed. We begin by partitioning the spatial domain (i.e. $0-360°$ on the TMA boundary) into discrete number of zones $z_k \in Z$, and the time horizon into discrete time steps $t_i \in T$. We also denote by $N_{i,k}$ the number of flights in zone z_k during time interval t_i .

为了检测终端区域内航班时间分布发生显著变化的时间点，遵循以下程序。我们首先将空间域 (即 TMA 边界上的 $0-360°$) 划分为离散的若干区域 $z_k \in Z$ ，并将时间范围划分为离散的时间步 $t_i \in T$ 。我们还用 $N_{i,k}$ 表示在时间间隔 t_i 内区域 z_k 内的航班数量。



06:00-11:00 11:00-16:00 19:00-22:00

Fig. 2. Polar histograms of the variation of arrivals/departures geographical distribution in the TMA in example consecutive periods.

图 2. 示例连续时间段内 TMA 到达/出发地理分布变化的极坐标直方图。

First, we define Change $_{i,k}$ to be a binary variable indicating whether a significant temporal change in demand is detected for zone z_k from time t_{i-1} to t_i ; that is,

首先，我们定义变化 $_{i,k}$ 为一个二进制变量，表示是否检测到区域 z_k 从时间 t_{i-1} 到 t_i 的需求发生显著的时间变化；即，

$$\text{Change }_{i,k}=\begin{cases}1, & \left|N_{i,k}-N_{i-1,k}\right| \geq T_1 \\ 0, & \text{otherwise}\end{cases} \tag{1}$$

where T_1 is a user-defined threshold. Then we count the total number of zones where a change in demand is detected, and compare it with another threshold T_2 :

其中 T_1 是用户定义的阈值。然后我们计算检测到需求变化的区域总数，并将其与另一个阈值 T_2 进行比较:

$$\text{Change }_{i}=\begin{cases}1, & \sum_k \text{Change }_{i,k} \geq T_2 \\ 0, & \text{otherwise}\end{cases} \tag{2}$$

where Change $_i$ indicates whether the demand pattern in the entire MAS TMA changes significantly from time t_{i-1} to t_i . The threshold values can be determined statistically for a given number of spatial and temporal steps by analyzing the distribution of the demand changes from historical data, and subsequently setting appropriate critical values. They can be also determined via an optimization procedure that maximizes the performance of the resulting clustering, while taking into account uncertainties in the dynamic traffic demands (Sidiropoulos et al., 2017).

其中 Change $_i$ 表示整个 MAS TMA 的需求模式是否从时间 t_{i-1} 到 t_i 显著变化。阈值可以通过分析历史数据中需求变化的分布，针对给定的空间和时间步数统计确定，然后设置适当的临界值。它们还可以通过一种优化过程确定，该过程最大化生成的聚类的性能，同时考虑动态交通需求中的不确定性 (Sidiropoulos 等人，2017 年)。

Naturally, t_{i-1} and t_i are assigned to the same temporal cluster if Change $_i=0$, meaning that the demand patters in these two periods are deemed similar. The procedure for creating the temporal clusters is summarized below.

自然地，如果 Change $_i=0$ ，则 t_{i-1} 和 t_i 被分配到同一个时间聚类中，这意味着这两个时期的需求模式被认为是相似的。创建时间聚类的过程如下所述。

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(1) Initially, define each time period $t_i \in T$ to be a temporal cluster.

(2) For $i=2,3,\ldots$, assign t_i to the temporal cluster containing t_{i-1} if Change $_i=0$

(3) Return the final temporal clusters when b is checked for every i .

3.2. Spatial clustering

3.2. 空间聚类

Section 3.1 provides a method of partitioning the time horizon into a number of disjoint temporal clusters, each one corresponding to a unique demand pattern. Further spatial clustering is needed in order to derive the dynamic routes for each airport and operational type. The flights that belong to each temporal cluster are segregated according to the following characteristics: (1) type of operation (arrival/departure); (2) relevant MAS airport; and (3) direction (angle) of entry/exit.

第 3.1 节提供了一种将时间范围划分为若干不相交时间聚类的方法，每个聚类对应一个独特的需求模式。为了得出每个机场和运营类型的动态路线，需要进一步进行空间聚类。属于每个时间聚类的航班根据以下特征进行分离:(1) 运营类型 (到达/出发)；(2) 相关的 MAS 机场；(3) 进入/离开的方向 (角度)。

The flights within each temporal cluster can be initially grouped into “arrival” or “departure” for each of the MAS airports. Subsequently, the flights within each resulting group (e.g. JFK-arrivals, EWR-departures, etc.) are further clustered according to the direction in which they enter or exit the TMA, using a K -means spatial clustering algorithm. The K -means algorithm is a center-based algorithm and an appropriate choice for this application, as the resulting cluster center marks the intercept of the dynamic route with the TMA boundary (i.e. the unimpeded terminal waypoint for that cluster). The optimal number of clusters K is selected using the gap criterion heuristic (Tibshirani et al.,2001). Fig. 3 illustrates the spatial clustering of flights on the TMA boundary; we note that routes R_4 and R_5 have a conflict, as the minimum distance required does not separate their corresponding fixes.

每个时间簇内的航班最初可以按每个 MAS 机场的“到达”或“出发”进行分组。随后，每个结果组内的航班 (例如 JFK-到达，EWR-出发等) 根据它们进入或离开 TMA 的方向进一步聚类，使用 K -均值空间聚类算法。K -均值算法是一种基于中心的算法，适合用于此应用，因为生成的簇中心标记了动态路线与 TMA 边界的交点 (即该簇的无障碍终端航点)。最佳簇数 K 是使用间隙准则启发式方法 (Tibshirani 等人，2001 年) 选择的。图 3 说明了在 TMA 边界上的航班空间聚类；我们注意到路线 R_4 和 R_5 存在冲突，因为所需的最小距离无法将它们对应的修正点分开。

The geometry of the TMA admits a maximum number of clusters corresponding to the maximum number of terminal waypoints $N_{\max} = \frac{2\pi R}{D_{\min}}$, rounded to the nearest integer below. Here, R is the TMA radius and $D_{\min}$ is the minimum separation distance between two adjacent terminal fixes. This constraint is taken into account in the clustering algorithm.

TMA 的几何形状允许的最大簇数对应于最大数量的终端航点 $N_{\max} = \frac{2\pi R}{D_{\min}}$ ，四舍五入到最接近的整数以下。在这里，R 是 TMA 半径，$D_{\min}$ 是两个相邻终端修正点之间的最小分离距离。这个约束在聚类算法中被考虑进去。

There are other ways to define the dynamic routes based on clustering, such as an integrated spatio-temporal 4-D clustering. However, the rationale for separated spatial and temporal clusters is to allow decoupled design/operation periods, such that each dynamic route is associated with exactly one well-defined time period. This is important as it provides flexibility for the decision maker in order to invoke different control strategies at different time periods of the day with clearly defined boundaries. On the other hand, an integrated 4-D clustering results in spatial and temporal coupling that leads to non-separable operation by either time or space. This would make the proposed framework less flexible and unlikely to be adopted in real-world operations.

基于聚类的方式定义动态路由还有其他方法，例如集成的四维时空聚类。然而，分离的时空聚类的理由是为了允许解耦的设计/操作周期，使得每条动态路由都与一个明确定义的时间周期相对应。这对于决策者来说很重要，因为它提供了在不同时间周期的日内调用不同控制策略的灵活性，并且边界清晰。另一方面，集成的四维聚类导致了时空耦合，使得无法通过时间或空间进行分离操作。这会使所提出的框架变得不够灵活，不太可能在现实世界的操作中被采用。

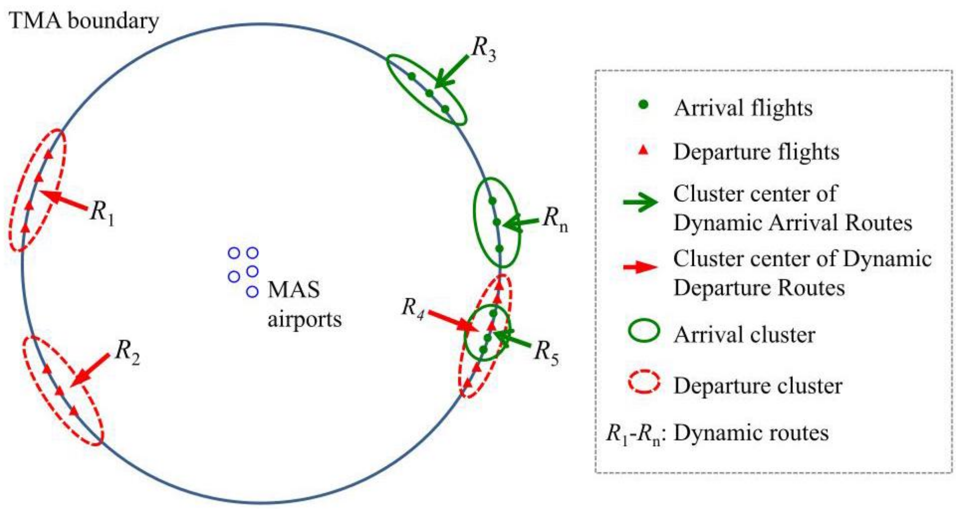

Fig. 3. Dynamic routes for arrivals and departures (Sidiropoulos et al., 2017).
图 3. 到达和出发的动态路由 (Sidiropoulos 等人，2017 年)。

The proposed spatio-temporal clustering approach can be applied to any given operational horizon. It is computationally efficient and can be applied to a variety of data sets with different levels of spatial and temporal resolution. Note that the choice of the threshold values T_1 and T_2 has an impact on the clustering results and, subsequently, on the 3-D routing problem. In fact, a detailed sensitivity analysis, as well as an optimization problem for the selection of the most appropriate threshold values, has been presented in Sidiropoulos et al. (2017). In that study, different clustering results were evaluated using the total sum of the distances of the individual flights from the centers of their assigned clusters. Moreover, spatiotemporal clustering in the presence of demand uncertainty was also addressed based on robust optimization.

所提出的时空聚类方法可以应用于任何给定的操作范围。它在计算上是高效的，并且可以应用于具有不同空间和时间分辨率的各种数据集。请注意，阈值 T_1 和 T_2 的选择对聚类结果有影响，进而对三维路由问题有影响。实际上，在 Sidiropoulos 等人 (2017 年) 的研究中，已经提出了详细的敏感性分析以及选择最合适阈值的最优化问题。在该研究中，通过计算单个航班与其指定聚类中心的距离总和来评估不同的聚类结果。此外，还基于鲁棒优化处理了需求不确定性下的时空聚类问题。

4. Three-dimensional routing within the terminal area

4. 终端区域内的三维路由

In the case of MAS terminal airspace design, arrival and departure routing falls under the category of the many-to-many shortest path problem, where many terminal waypoints need to be connected to multiple airports (runways) in the most efficient manner. However, given the design objectives set out in this paper (i.e. all routes should be conflict-free to ensure safety and reduce controller workload), the many-to-many routing problem has certain limitations. Specifically, solving for all the routes simultaneously could:

在 MAS 终端空域设计中，到达和出发路由属于多对多最短路径问题的范畴，其中许多终端航点需要以最高效的方式连接到多个机场 (跑道)。然而，鉴于本文设定的设计目标 (即所有路由都应无冲突以确保安全并减轻管制员的工作负担)，多对多路由问题存在一定的局限性。具体来说，同时解决所有路由可能会导致:

- Lead to poor route geometries, as routes that need to use the same airspace would have to make additional horizontal and vertical turns to satisfy the conflict-free constraint. This reduces the smoothness of the routes and may result in operational infeasibility;
- 导致路由几何形状不良，因为需要使用相同空域的路由必须进行额外的水平和垂直转向以满足无冲突约束。这降低了路由的平滑性，可能导致操作不可行；
- Significantly increase computational complexity and resource requirements; and
- 显著增加计算复杂性和资源需求；
- Ignore information on a decision maker’s preference or a priori requirements.
- 忽略决策者的偏好或先验要求。

To overcome these limitations, the routing problem is formulated as a sequence of constrained shortest path problem based on route priorities, to be derived from several qualitative and quantitative characteristics. In turn, the main benefits of this lexicographic optimization approach include the following:

为了克服这些局限性，路由问题被公式化为基于路由优先级的约束最短路径问题序列，该序列将从几个定性和定量特征中导出。反过来，这种词典式优化方法的主要好处包括以下内容:

- The sequentially solved one-to-one constrained shortest path problem yields much more smooth route geometries with fewer horizontal and vertical turns compared to solving all the routes simultaneously. This is desirable from a route feasibility perspective as well as from the need to reduce air traffic controllers’ workload.
- 顺序解决的一对一约束最短路径问题与同时解决所有路由相比，产生了更加平滑的路由几何形状，水平和垂直转向更少。从路由可行性和减轻空中交通管制员工作负担的角度来看，这是理想的。
- The lexicographic solution procedure is computationally tractable, as it suffices to solve a set of one-to-one constrained shortest path problems. Computational efficiency becomes increasingly pronounced when the number of dynamic routes increases.
- 词典式解决方案程序在计算上是可行的，因为只需要解决一组一对一的约束最短路径问题。当动态路由数量增加时，计算效率变得越来越显著。
- The lexicographic approach requires a ranking of the dynamic routes, which naturally caters to the need to reflect the decision maker’s preferred routes. This is achieved via the analytic hierarchy process model.

- 词典式方法需要对动态路由进行排名，这自然满足了反映决策者偏好路由的需求。这是通过层次分析法模型实现的。

We start with a formal formulation of the multi-objective optimal routing problem in Section 4.1. 我们从第 4.1 节的多目标最优路由问题的正式公式开始。

4.1. Analytical formulation of the optimal routing problem

4.1. 最优路由问题的分析公式化

The TMA route design problem consists of two parts: (i) a terminal fix selection problem on the TMA boundary (as motivated by the potential conflict among dynamic routes illustrated in Fig. 3), and (ii) a 3-D routing problem within the

TMA 航线设计问题包括两部分:(i) TMA 边界上的终端固定点选择问题 (如图 3 所示的动态航线之间潜在的冲突所驱动)，以及 (ii) TMA 内部的 3D 路由问题。

TMA. The purpose of such a design is to serve the demands along the dynamic routes in the most cost-effective way. These two sub-problems are detailed below.

这样的设计目的是以最高成本效益的方式服务于动态航线沿线的需求。下面详细说明这两个子问题。

4.1.1. Terminal fix selection problem formulation

4.1.1. 终端固定点选择问题公式化

The terminal fix selection problem, which precedes the 3-D routing problem, can be formulated as follows. We let ξ_i be the location on the TMA boundary that corresponds to the ith dynamic route (e.g. the cluster centers in Fig. 3). Due to potential conflict among different dynamic routes, a subset of these routes needs to be relocated along the TMA boundary. Denoting the relocated fix for the i th dynamic route by $\bar{\xi}_i$, the terminal fix selection problem aims to solve:

终端固定点选择问题，位于 3D 路由问题之前，可以如下公式化。我们让 ξ_i 表示 TMA 边界上与第 i 条动态航线相对应的位置 (例如图 3 中的簇中心)。由于不同的动态航线之间可能存在潜在的冲突，需要将其中一部分航线沿 TMA 边界重新定位。用 $\bar{\xi}_i$ 表示第 i 条动态航线的重新定位固定点，终端固定点选择问题旨在解决:

$$\min_{\bar{\xi}_i}\left[\operatorname{dist}\left(\xi_1,\bar{\xi}_1\right),\operatorname{dist}\left(\xi_2,\bar{\xi}_2\right),\ldots,\operatorname{dist}\left(\xi_i,\bar{\xi}_i\right),\ldots,\operatorname{dist}\left(\xi_n,\bar{\xi}_n\right)\right]^T\in\mathbb{R}^n \tag{3}$$

$$\text{Subject to dist }\left(\bar{\xi}_i,\bar{\xi}_j\right)\geq\Delta,\forall i\neq j$$

where $\operatorname{dist}(\cdot,\cdot)$ denotes the distance between two fixes on the TMA boundary, Δ is the minimum separation. The meaning of Eq. (3) is quite clear: in relocating the fixes, we aim to minimize their displacements (in the interest of minimum flying distance), while maintaining the minimum separation among all the relocated fixes.

其中 $\operatorname{dist}(\cdot,\cdot)$ 表示 TMA 边界上两个固定点之间的距离，Δ 是最小间隔。方程 (3) 的含义非常清楚: 在重新定位固定点时，我们旨在最小化它们的位移 (为了最小飞行距离)，同时保持所有重新定位的固定点之间的最小间隔。

Remark. Formulation of Eq. (3) applies to any TMA boundary geometry and the distance measure between two fixes. In the simplified case of a circular boundary with radius R , the location of the fixes can be parameterized by the angle θ based on polar coordinates, and the distance between two fixes θ_1 and θ_2 reduces to $|\theta_1-\theta_2|R$.

备注。方程 (3) 的公式适用于任何 TMA 边界几何形状以及两个固定点之间的距离度量。在圆形边界 (半径为 R) 的简化情况下，固定点的位置可以通过极坐标的角度 θ 来参数化，两个固定点 θ_1 和 θ_2 之间的距离简化为 $|\theta_1-\theta_2|R$ 。

4.1.2. 3-D routing problem formulation

4.1.2. 3D 路由问题公式化

For the 3-D routing problem, the objective is to minimize the travel distances [3] of all the dynamic routes within the TMA. There are multiple ways of mathematically representing a route in the 3-D Euclidean space, e.g. using Cartesian or polar coordinates. In view of the flying and maneuvering characteristics of the aircraft, we propose a novel representation illustrated in Fig. 4.

对于三维路由问题，目标是最小化所有动态路由在 TMA 内的行驶距离 [3] 。在三维欧几里得空间中，有多种方式可以用数学表示一条路由，例如使用直角坐标或极坐标。考虑到飞机的飞行和机动特性，我们提出了一种新颖的表示方法，如图 4 所示。

In Fig. 4, the dynamic route (for arrival) consists of a sequence of points connecting the fix on the TMA boundary to the runway. At each intermediate point, the next point along the route is defined via a horizontal and vertical change in the heading with a discrete number of angles (with increments β and δ , respectively) and the fixed track distance (d and I , respectively). Notice that the ranges of the angles (i.e. α and γ) depend on the maneuvering capabilities of the aircraft, altitude/speed and type of operation (arrival/departure) associated with the dynamic route. Similar representation can be defined for departure routes.

在图 4 中，动态路由 (用于到达) 由一系列连接 TMA 边界上的固定点与跑道的点组成。在每个中间点，通过航向的水平变化和垂直变化 (分别以 β 和 δ 的增量) 以及固定的航迹距离 (分别对应 (d 和 I) 定义沿路由的下一个点。注意，角度的范围 (即 α 和 γ) 取决于飞机的机动能力、高度/速度以及与动态路由相关的操作类型 (到达/起飞)。

For a given dynamic route, we let H and V be the discrete sets of horizontal and vertical turning angles, respectively, and let N be the number of intermediate points along the route. Then the 3-D dynamic route r can be uniquely represented as a sequence of segments:

对于给定的动态路由，我们令 H 和 V 分别为水平和垂直转向角度的离散集合，并令 N 为路由上的中间点的数量。那么，三维动态路由 r 可以唯一地表示为一系列线段的序列:

$$r=\left(z_1, z_2, \ldots, z_n\right) \in \mathbb{R}^{2 \times n} \text { where } z_i=\left(h_i, v_i\right)^T \in H \times V \tag{4}$$

We further define the distance between two routes $\operatorname{dist}\left(r_1, r_2\right)$ to be the minimum Euclidean distance between any two points from the two routes. Moreover, for any external area ω represented as a subset of the 3-dimensional Euclidean space, we similarly define its distance from a route $\operatorname{dist}(r, \omega)$. Then, the optimization problem for the 3-D routing can be formulated as:

我们进一步定义两条路由 $\operatorname{dist}\left(r_1, r_2\right)$ 之间的距离为这两条路由上任意两点之间的最小欧几里得距离。此外，对于任何表示为三维欧几里得空间子集的外部区域 ω ，我们同样定义它到路由 $\operatorname{dist}(r, \omega)$ 的距离。然后，三维路由的优化问题可以表述为:

$$\min \left[F\left(r_1\right), F\left(r_2\right), \ldots, F\left(r_n\right)\right] \in \mathbb{R}^n \tag{5}$$

$$\text{Subject to dist }\left(r_i, r_j\right) \geq \Delta, \forall 1 \leq i \neq j \leq n, \operatorname{dist}\left(r_i, \omega\right) \geq \Delta, \forall 1 \leq i \leq n, \forall \omega \in \Omega$$

where $F\left(r_i\right)$ denotes the travel distance of the i th dynamic route, Ω is the set of external areas to be avoided by the dynamic routes (e.g. no-fly zones, high terrain, noise and emission sensitive areas, and convective weather)

其中 $F\left(r_i\right)$ 表示第 i 条动态路线的行驶距离，Ω 是动态路线需要避开的外部区域集合 (例如禁飞区、高地形、噪声和排放敏感区域以及对流天气影响的区域)

The Multi-Objective Optimization (MOO) problem (4)-(5) explicitly takes into consideration the following operational constraints:

多目标优化 (MOO) 问题 (4)-(5) 明确考虑以下运营约束:

1. Horizontal and vertical separation between any two dynamic routes for safety reasons and for embracing the conflict-free concept;

1. 出于安全考虑以及采纳无冲突概念，任意两条动态路线之间的水平和垂直间隔；

2. External spatial constraints such as airspace restrictions and areas influenced by convective weather; and

2. 外部空间约束，如空域限制和受对流天气影响的区域；以及

3. Aircraft performance (maneuverability capabilities), which precludes unrealistic flight maneuvers following certain route design.

3. 飞机性能 (机动能力)，这排除了在特定路线设计后进行不切实际的飞行机动。

To reduce the complexity of the MOO problem in the search for a satisfactory solution, we adopt a Lexicographic Multi-Objective Optimization (LMOO) approach by solving the individual objectives in (5) sequentially following an a priori preference order, to be derived in Section 4.2 using a novel AHP route prioritization model. Previous research has followed a similar approach (Zhou et al. 2014; Pfeil, 2011) for single-airport terminal routing, but selecting an arbitrary preference order and failing to account for the full range of operational characteristics encountered in a Metroplex.

为了降低在寻找满意解时 MOO 问题的复杂性，我们通过依次解决 (5) 中的单个目标，并遵循先验偏好顺序，采用字典序多目标优化 (LMOO) 方法，该偏好顺序将在第 4.2 节中使用一种新颖的层次分析法 (AHP) 路线优先级模型导出。之前的研究 (Zhou et al. 2014; Pfeil, 2011) 在单一机场终端路由中采用了类似方法，但是选择了任意的偏好顺序，并且未能考虑在 Metroplex 遇到的全部运营特性。

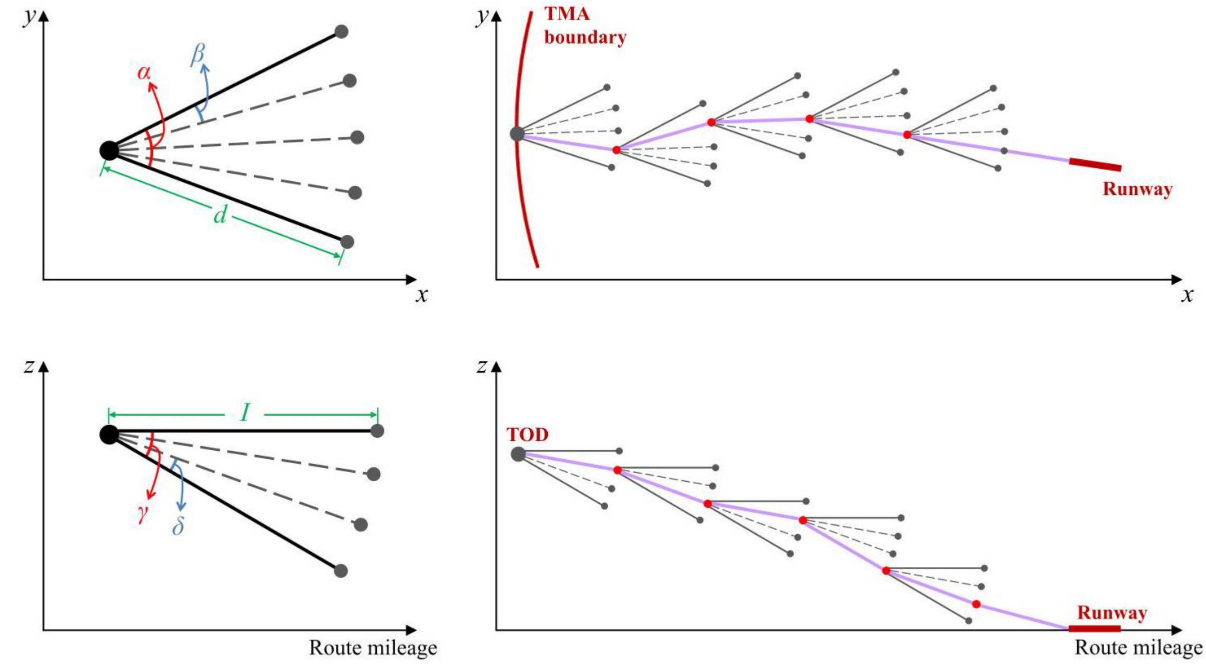

Fig. 4. Representation of 3-D route (arrival) in the TMA.

图 4. TMA 中的三维路线 (进近) 表示。

Given the sorted set of objectives $\{F(r_k), k=1,\ldots,n\}$ in a decreasing order of importance, the LMOO solves the following sub-problems sequentially:

给定按重要性递减顺序排列的目标集合 $\{F(r_k), k=1,\ldots,n\}$ ，LMOO 依次解决以下子问题:

$$\left.\begin{array}{c}\min F(r_k)\\ \text{s.t. } \operatorname{dist}(r_i, r_k)\geq\Delta, \forall 1\leq i<k, \operatorname{dist}(r_k,\omega)\geq\Delta, \forall\omega\in\Omega\end{array}\right\} \text{Sub- problem } k,\ k=1,2,\ldots,n \tag{6}$$

In other words, the LMOO solves for the most important route first, then uses it as an additional constraint when solving for the second important route, and this procedure carries on for the rest of the routes. In this process the routes are designed sequentially and the feasible set is constantly updated and becomes more stringent.

换句话说，LMOO 首先解决最重要的路线，然后将其作为解决第二重要路线时的附加约束，并以此类推，直至其余路线。在此过程中，路线是依次设计的，可行集不断更新并变得更加严格。

Following such a LMOO approach, the rest of Section 4 is organized as follows. Section 4.2 derives the route priorities based on the AHP and several qualitative and quantitative characteristics. Section 4.3 details the solution procedure for the terminal fix selection problem based on the derived priorities. Finally, Section 4.4 carries out the LMOO procedure in the design of the 3-D routes within the TMA using a modified A^* algorithm.

objectives, such as flying time and fuel burnt.

目标，如飞行时间和燃油消耗。

采用这样的 LMOO 方法，第 4 节其余部分的组织如下。第 4.2 节基于层次分析法 (AHP) 和若干定性和定量特征推导路线优先级。第 4.3 节详细说明了基于推导出的优先级来解决终端固定选择问题的解决过程。最后，第 4.4 节使用修改后的 A^* 算法，在 TMA 内的 3-D 路由设计中执行 LMOO 过程。

4.2. Route prioritization based on analytic hierarchy process

4.2. 基于层次分析法的路线优先级确定

To rank the dynamic routes while taking into account a range of qualitative and quantitative characteristics of Metroplex operations, we propose an enhanced Analytic Hierarchy Process (AHP) model in this section. The AHP is a multi-criteria decision making technique that seeks to decompose a complex decision into a series of pair-wise comparisons between criteria that are considered important to achieve a specific goal (Saaty, 1990). It can incorporate both quantitative and qualitative information into the decision-making process, while allowing the weights or priorities of relevant factors to be derived from expert knowledge. The AHP is a powerful tool and an adequate approach for enhancing the decision-making process in MAS; however, to date it has had very limited application in ATM and, to the authors' knowledge, has not been used for terminal airspace routing. There have been numerous prior applications of the AHP in ATM. Asfe et al. (2014) used the AHP to combine and rank the key empirical factors that influence air traffic delays. Lintner et al. (2009) developed the Aerospace Performance Factor (APF) based on the AHP for the assessment of safety performance using a range of localized safety measures, such as reported safety incidents, which were in turn weighted by experts and normalized against system operations. Di Gravio et al. (2014) used AHP to develop reactive and proactive indicators to predict future safety critical situations to aid decision-making. Finally, AHP has been used in design problems such as routing (Sattayaprasert et al., 2008), the testing of new ATM CONOPS (Castelli and Pellegrini, 2011) and ATM en-route airspace structure design (Cong et al., 2011). The proposed AHP model employed in this paper is illustrated in Fig. 5 and elaborated below.

为了在考虑大都市区运营的各种定性和定量特征的情况下对动态路线进行排序，我们在本节提出了一个增强的层次分析法 (AHP) 模型。层次分析法是一种多标准决策技术，旨在将复杂的决策分解为一系列关于被认为对实现特定目标重要准则的两两比较 (Saaty，1990)。它可以将定量和定性的信息融入决策过程，同时允许从专家知识中得出相关因素的权重或优先级。AHP 是一种强大的工具，也是提高多代理系统 (MAS) 决策过程的有效方法；然而，迄今为止它在空管领域 (ATM) 的应用非常有限，据作者所知，尚未用于终端空域路由。之前已有许多在空管领域应用 AHP 的案例。Asfe 等人 (2014) 使用 AHP 结合并排序影响航空交通延误的关键实证因素。Lintner 等人 (2009) 基于 AHP 开发了航空航天性能因子 (APF)，用于通过一系列本地化安全措施 (如报告的安全事件) 评估安全性能，这些措施又由专家加权并针对系统运营进行标准化。Di Gravio 等人 (2014) 使用 AHP 开发了预测未来关键安全情况的反应性和预防性指标，以辅助决策。最后，AHP 已被应用于设计问题，如路由 (Sattayaprasert 等，2008)、新的空管概念 (CONOPS) 测试 (Castelli 和 Pellegrini，2011) 以及空管航路空域结构设计 (Cong 等，2011)。本文提出的 AHP 模型在图 5 中有所说明，以下将详细阐述。

The AHP can be described by the following steps:

AHP 可以通过以下步骤进行描述:

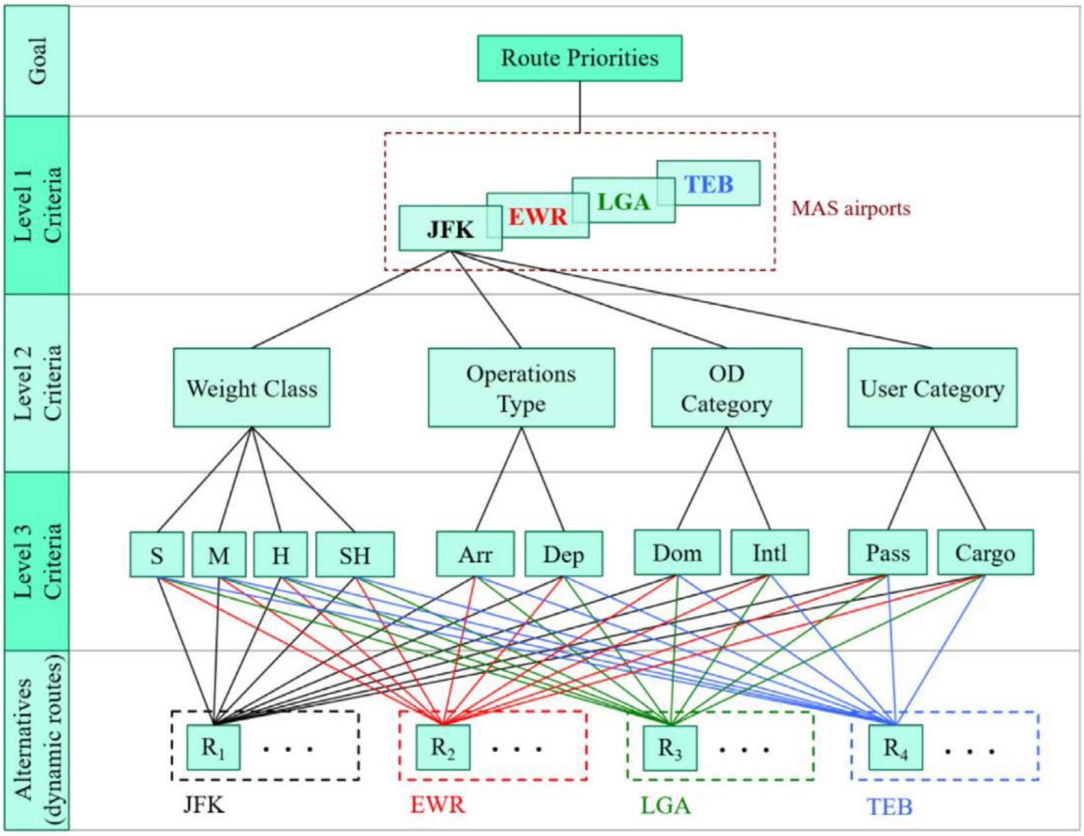

Fig. 5. Illustration of the AHP model (New York Metroplex example).
图 5. 层次分析法 (AHP) 模型示例 (纽约大都市区示例)。
1 Define the objective of the decision process;
1 确定决策过程的目标;
2 Decompose the objective into elements, based on their common characteristics; and
2 根据它们的共同特征，将目标分解为元素;
3 Organize the elements into levels according to their relative importance in a top-down scheme
3 按照元素在自上而下方案中的相对重要性，将元素组织成层级;

The nodes in Fig. 5 represent the criteria or the alternatives (i.e. dynamic routes), while the links indicate their relationships. The highest level in the hierarchy is the goal, which is to prioritize and rank the dynamic routes. At the first level, the routes are assessed solely based on their relevant MAS airports. [4] The second level consists of criteria describing the aircraft mix. In particular, "Weight class" is based on the ICAO standard and refers to the number of small (S), large (L), heavy (H), and super-heavy (SH) aircraft on each route. "Operations Type" refers to the number of arrivals or departures on a given route. The "OD category" distinguishes domestic and international flights, while the "User category" identifies the number of passenger and cargo aircraft. Finally, all the dynamic routes are identified at the bottom level. To use the AHP model, the decision maker needs to pairwise compare the elements at each level with respect to their parent node. The AHP model proposed here has been validated by SMEs from the PANYNJ using the Saaty scale (Saaty, 1990).

图 5 中的节点代表准则或备选方案 (即动态路线)，而链接表示它们之间的关系。层次结构中的最高层是目标，即优先并排列动态路线。在第一层，路线仅根据它们相关的 MAS 机场进行评估。[4] 第二层由描述飞机混合的准则组成。特别是，“重量类别”基于国际民航组织 (ICAO) 标准，并指的是每条路线上的小型 (S)、大型 (L)、重型 (H) 和超重型 (SH) 飞机的数量。“运营类型”指的是在给定路线上到达或出发的数量。“OD 类别”区分国内和国际航班，而“用户类别”识别乘客和货运飞机的数量。最后，所有动态路线都在最底层标识。要使用 AHP 模型，决策者需要针对每个层级的元素进行成对比较，相对于它们的父节点。这里提出的 AHP 模型已经通过使用 Saaty 标度 (Saaty，1990) 的 PANYNJ 中小企业 (SMEs) 进行了验证。

The developed AHP model combines both the qualitative and quantitative characteristics that affect operations in MAS. The decision maker is called upon to conduct pairwise comparisons for all the different hierarchies in the model. Once the comparisons are complete, the quantitative characteristics of the elements that comprise the alternatives (the "dynamic routes") are obtained. The relative weights (eigenvectors) of the examined factors are then calculated based on the eigenvalue approach. To articulate this procedure mathematically, we let matrix A be the pointwise reciprocal of the pairwise comparison matrix. We consider the following eigenvalue problem:

开发的 AHP 模型结合了影响 MAS 操作的定性和定量特征。决策者需要对模型中所有不同的层次进行成对比较。比较完成后，可以得到构成选择方案 (" 动态路线") 的元素的定量特征。然后基于特征值方法计算所考察因素的相对权重 (特征向量)。为了从数学上阐述这一过程，我们设矩阵 A 为成对比较矩阵的点对点倒数。我们考虑以下特征值问题:

$$Aw = \lambda_{\max} w, e^T w = 1 \tag{7}$$

where w is the vector of ratio-scale priority weights, $\lambda_{\max}$ is the principal eigenvalue of the matrix A and e^T is a unit row vector (Saaty, 1990). Consequently, the decision maker's judgments need to be evaluated for their consistency. The consistency of the matrix A is addressed by calculating the Consistency Index(CI):

其中 w 是比例尺度优先权重向量，$\lambda_{\max}$ 是矩阵 A 的主特征值，e^T 是单位行向量 (Saaty，1990)。因此，决策者的判断需要对其一致性进行评估。矩阵 A 的一致性通过计算一致性指数 (CI) 来解决:

$$CI = \frac{\lambda_{\max} - n}{n - 1} \tag{8}$$

where n is the order of the matrix. Cl is then used to generate the Consistency Ratio $CR = Cl/RI$, where RI is the Random Index generated by Saaty for a very large sample of randomly populated matrices. In order for the assessment to be complete,

其中 n 是矩阵的阶数。Cl 然后用于生成一致性比率 $CR = Cl/RI$ ，其中 RI 是 Saaty 为大量随机填充矩阵生成的随机指标。为了使评估完整，

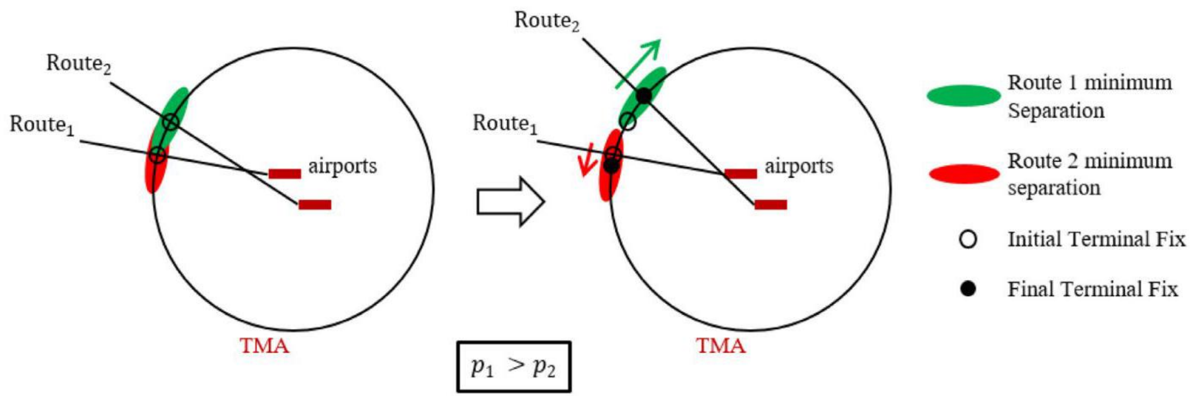

Fig. 6. Priority-based re-positioning of dynamic routes. The terminal fix corresponding to route with higher priority ($\mathbf{p}_1$) has smaller displacement compared to the terminal fix corresponding to route with lower priority ($\mathbf{p}_2$) .

图 6. 基于优先级的动态路线重新定位。相对于优先级较低的路线 ($\mathbf{p}_2$) 的终端修正，优先级较高的路线 ($\mathbf{p}_1$) 的终端修正位移较小。

the CR should be no greater than 0.10 (both CI and CR are unitless). Otherwise, the decision makers should revisit their assessment to improve consistency (Saaty, 1990).

CR 应该不大于 0.10(CI 和 CR 都是无量纲的)。否则，决策者应该重新审视他们的评估以改进一致性 (Saaty，1990)。

The weights derived for each of the criteria levels (levels 1-3 in Fig. 5) are used to calculate the priorities of the dynamic routes using the referenced AHP method (Schoner and Wedley, 1989) to account for the proportionality between the criteria and their relevant options. The proportionality condition is enforced by the inclusion of a constant K to account for this:

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4 Specific airports may be deemed of higher importance than others. Alternatively, the number of origin/destination pairs that each airport serves may be used for this assessment.

4 某些机场可能被认为比其他机场更重要。或者，每个机场服务的始发/目的地对的数量也可以用于此评估。

为每个标准级别 (图 5 中的 1-3 级) 得出的权重用于通过参考 AHP 方法 (Schoner 和 Wedley，1989 年) 计算动态路线的优先级，以考虑标准与其相关选项之间的比例关系。比例条件通过包含一个常数 K 来实现:

$$x_k = K \cdot q_k \cdot \sum_h T_{h,k} \tag{9}$$

where

其中

x_k is the importance of criterion k with respect to the objective

x_k 是相对于目标的标准 k 的重要性

q_k is a scale factor which converts measurement on criterion k to units of the objective

q_k 是一个比例因子，它将标准 k 上的度量转换为目标的单位

$T_{h,k}$ is the absolute measurement of option h on criterion k

$T_{h,k}$ 是选项 h 在标准 k 上的绝对度量

The referenced AHP is selected in this paper as it accounts for proportionality effects under different criteria. The final priorities are calculated as a weighted sum based on the derived weights for different criteria at various levels in the hierarchy. The detailed derivation of the priorities is presented in Appendix A.

本文选择引用的 AHP 方法，因为它考虑了不同标准下的比例效应。最终优先级是基于层次结构中不同级别不同标准的导出权重计算的加权总和。优先级的详细推导在附录 A 中呈现。

The hierarchy structured in this model is developed on the basis of the literature relating to airport and MAS operations; and the subsequent criteria are validated by seven SMEs. These SMEs represent different stakeholders including air traffic controllers, air navigation service providers and airport authorities (e.g. the PANYNJ, the NY airports and the FAA) with more than 20 years of experience in air traffic control facilities and airport operations. The validation process was based on questionnaires and semi-structured face-to-face interviews. The questionnaires addressed various issues of Metroplex operations and their structure aimed to enable the SMEs to identify inefficiencies in Metroplex systems. Conducting the interviews face-to-face enabled the interviewees to highlight additional areas important to MAS operations there were not covered in the initial questionnaires. The identified characteristics were combined into the AHP model presented in this paper. The SMEs assessed the structure of the proposed AHP model for:

该模型中的层次结构是基于与机场和 MAS 运营相关的文献开发的；随后，通过七位行业专家 (SMEs) 验证了标准。这些 SMEs 代表不同的利益相关者，包括空中交通管制员、空中导航服务提供商和机场管理局 (例如 PANYNJ、纽约机场和 FAA)，他们在空中交通管制设施和机场运营方面拥有超过 20 年的经验。验证过程基于问卷调查和半结构化面对面访谈。问卷调查涉及 Metroplex 运营的各种问题，其结构旨在使 SMEs 能够识别 Metroplex 系统中的低效环节。面对面进行访谈使受访者能够突出 MAS 运营中最初问卷未涵盖的额外重要领域。识别的特征被整合到本文中提出的 AHP 模型中。SMEs 对所提出 AHP 模型的结构进行了评估:

(1) Completeness of the hierarchy, hierarchy levels, and criteria (elements) to capture the several operational characteristics that currently affect management decisions; and

(1) 层级完整性的完备性，层级及其标准 (要素) 以捕捉当前影响管理决策的多个运营特性；

(2) Representativeness of the hierarchy order and AHP structure to reflect current decision-making order of importance.

(2) 层级顺序和层次分析法 (AHP) 结构的代表性，以反映当前决策重要性的顺序。

After the validation of the AHP structure, the SMEs were asked to conduct pairwise comparisons of different levels of the hierarchy for a given test period (see Appendix B for some examples of the AHP pairwise comparison). The AHP results for the NY case study are presented in Section 5.2.

在验证 AHP 结构之后，要求中小企业 (SMEs) 对给定测试期的层级不同层次进行成对比较 (参见附录 B 中 AHP 成对比较的一些示例)。纽约案例研究的 AHP 结果在 5.2 节中呈现。

The proposed prioritization approach also accounts for the competition between different airports for airspace capacity, as the airport-specific objectives are factored into the AHP model and are directly associated with the dynamic demand characteristics at the corresponding level of the hierarchy. This yields a centralized assignment while allowing for particular push strategies to be implemented for each airport.

提出的优先级排序方法还考虑了不同机场之间为空域容量进行的竞争，因为机场特定目标被纳入 AHP 模型，并且与层级相应级别的动态需求特性直接相关。这产生了一个集中分配，同时允许为每个机场实施特定的推送策略。

4.3. Priority-based terminal fix selection model

4.3. 基于优先级的终端固定点选择模型

This section determines the points of entry/exit on the TMA boundary for the dynamic routes, by resolving the potential conflicts (e.g. see Fig. 3) according to the derived priorities. In other words, we aim to assign each dynamic route to a unique terminal fix on the boundary while satisfying the minimum separation constraint; and we do so by minimizing the displacements between the initial entry/exit points (given by the cluster centers as shown in Fig. 3) and the final fixes.

本节通过解决潜在的冲突 (例如，见图 3)，根据得出的优先级确定动态路由在 TMA 边界的进出点。换句话说，我们的目标是将在边界上的每个动态路由分配到一个唯一的终端固定点，同时满足最小间隔约束；我们通过最小化初始进出点 (由图 3 所示的簇中心给出) 与最终固定点之间的位移来实现这一点。

We begin by describing the procedure for resolving two conflicting dynamic routes (see Fig. 6 for an illustration). When the distance between their entry/exit points is less than the minimum separation, the two dynamic routes need to be kept apart from each other with their precise displacements dependent on their relative priorities. Specifically, let p_1 and p_2 be the priorities of routes 1 and 2, respectively, $d_{1,2}\,(<\Delta)$ be the distance between their current entry/exit points where Δ denotes the minimum separation. The inverse distance weighted method is used to calculate the displacements of the two routes:

我们首先描述解决两个冲突动态路由的过程 (见图 6 的说明)。当它们的入口/出口点之间的距离小于最小间隔时，这两个动态路由需要彼此保持一定的距离，它们的确切位移取决于它们的相对优先级。具体来说，设 p_1 和 p_2 分别为路由 1 和路由 2 的优先级，$d_{1,2}\,(<\Delta)$ 为它们当前入口/出口点之间的距离，其中 Δ 表示最小间隔。使用逆距离加权方法来计算两条路由的位移:

$$\Delta x_1 = \frac{\Delta - d_{1,2}}{1+\frac{p_1}{p_2}}, \Delta x_2 = \frac{\Delta - d_{1,2}}{1+\frac{p_2}{p_1}} \tag{10}$$

Table 1
表 1
Parameters used in the state space search schemes.
状态空间搜索方案中使用的参数。

State space search scheme	Traversal step (km)	Horizontal angle increment (°)	Max number of horizontal increments	Vertical angle increment (°)	Max number of vertical increments
I (arrivals)	3	2	6	1	3
II (arrivals)	3	2	5	1	3
III (departures)	3	2	6	1	4
IV (departures)	3	2	5	1	4

状态空间搜索方案	跨越步长 (公里)	水平角度增量 (°)	水平增量最大数量	垂直角度增量 (°)	垂直增量最大数量
I(到达)	3	2	6	1	3
II(到达)	3	2	5	1	3
III (出发)	3	2	6	1	4
IV (出发)	3	2	5	1	4

Obviously, the route with higher priority has smaller displacement. Fig. 6 explains the aforementioned procedure intuitively. In order to ensure that the minimum separation is met for any neighboring fixes on the boundary of the TMA, an iterative rearrangement method is developed as follows. We examine all the points in sequence in a rearrangement cycle, repositioning a pair according to (10) whenever the minimum separation is violated. After all the pairs of fixes on the rearrangement cycle are visited, we repeat this procedure as long as at least one change has been made within the previous cycle, i.e. we stop immediately after a full rearrangement cycle runs without reallocating any of the fixes.

显然，优先级较高的路由位移较小。图 6 直观地解释了上述过程。为了确保 TMA 边界上任何相邻修正点满足最小间隔，开发了一种迭代重排方法如下。我们按顺序检查重排周期中的所有点，每当违反最小间隔时，根据 (10) 重新定位一对点。在访问完重排周期上的所有修正点对之后，只要在之前的周期中至少进行了一次更改，我们就重复这个过程，即在一个完整的重排周期运行完毕且没有重新分配任何修正点后立即停止。

Clearly, this formulation poses a straightforward limitation to the maximum number of terminal fixes, beyond which the problem becomes infeasible. Thus, appropriate constraints need to be applied to both the minimum separation distance and the maximum number of terminal fixes.

显然，这种公式对终端修正点的最大数量提出了直接的限制，超出这个限制，问题将变得不可行。因此，需要同时对最小间隔距离和最大终端修正点数量应用适当的约束。

4.4. Lexicographic multi-objective optimization for 3-D routing

4.4. 词典式多目标优化在三维路由中的应用

The priority-based terminal fix selection model presented above assigns the dynamic routes to their optimal entry/exit locations at the TMA boundary. The next step is to design the actual 3-D paths that aircraft follow within the terminal area. This design has to fulfill the following criteria: enable strategic de-confliction between different routes, minimize deviation from the shortest paths, accommodate additional traffic flow management initiatives, and provide feasible solutions that can be integrated into the current ATM system structure while enabling the future ATM system concepts outlined in SESAR and NextGEN (FAA, 2013). The 3-D conflict-free routes are designed according to the LMOO approach. The constrained routing problem for each dynamic route is solved using a modified A^* algorithm, which uses a parameterized state space search scheme to account for different aircraft maneuvering capabilities and internal/external constraints.

上述基于优先级的终端固定修正选择模型将动态路由分配到其在 TMA 边界的最优进出口位置。下一步是设计飞机在终端区域内实际遵循的 3-D 路径。该设计必须满足以下标准: 能够在不同路由间实现战略性的冲突解除，最小化偏离最短路径，适应额外的交通流量管理倡议，并提供可行的解决方案，这些方案可以整合到当前的空管系统结构中，同时能够实现 SESAR 和 NextGEN(FAA，2013) 中概述的未来空管系统概念。3-D 无冲突路由是根据 LMOO 方法设计的。每个动态路由的受限路由问题通过修改后的 A^* 算法解决，该算法使用参数化状态空间搜索方案来考虑不同飞机的机动能力以及内部/外部约束。

The design of the flight paths for arrival and departure operations can be formulated as a state space search problem, with the location of the aircraft being represented by a state in the graph and the arrival or departure path represented by a tree in the same graph $G(N, E)$ where E is the set of edges representing the flight paths (see Fig. 4). The following parameters are essential to fully describe the state of the aircraft:

到达和出发操作的飞行路径设计可以构建为状态空间搜索问题，飞机的位置在图中表示为状态，到达或出发路径表示为同一图中的树 $G(N, E)$ ，其中 E 是表示飞行路径的边集 (见图 4)。以下参数对于完整描述飞机状态至关重要:

- The current azimuth or bearing: the angle from the north that reveals the current direction of movement
- 当前方位角或方位: 从北方开始的角度，揭示了当前移动的方向
- The current zenith angle: the vertical angle between the vertical and the current direction of movement
- 当前天顶角: 垂直线与当前移动方向之间的垂直角度
- The current 3-D coordinates: expressed in latitude, longitude and altitude
- 当前 3-D 坐标: 以纬度、经度和高度表示

The successor operator determines the transition of an aircraft from a given node to a successor node. Such a transition depends on the current direction of movement (horizontally and vertically) and can be expressed in terms of increments of the horizontal and vertical turning angles with a maximum given by the current state of the aircraft. To reflect the operational characteristics of the aircraft, the successor nodes are parameterized by the incremental and maximum horizontal and vertical angles for traversing a given track distance; see Fig. 4 for an illustration.

后继操作符决定了飞机从一个给定节点到后继节点的过渡。这种过渡依赖于当前的移动方向 (水平和垂直)，并且可以用水平和垂直转向角的增量来表示，其最大值由飞机的当前状态决定。为了反映飞机的作战特性，后继节点通过给定航迹距离的增量和最大水平与垂直角度参数化；见图 4 的示例。

As shown in Fig. 4, for a given aircraft location, the number of nodes indicating its next potential location can be determined based on the parameters used for the successor operator (e.g. $\alpha, \beta, \gamma, \delta, d, I$). These parameters depend on the type of aircraft and are expressed by the corresponding ascent and descent rates that can be found in the Base of Aircraft Data (BADA) (Nuic, 2010). Moreover, aircraft performance varies depending on the (1) altitude/speed and (2) the type of operation (e.g. arrival/departure). In order to capture the aircraft maneuverability as realistically as possible, from a meso-scopic perspective (in contrast to microscopic perspective, which employs a mass-based model for aircraft dynamics), four different successor operator functions are developed (designated as StateSpaceSearch functions ranging

I-IV, see Table 1). The successor nodes are generated according to the corresponding function depending on the status of the current parent node. This allows, for example, steeper horizontal maneuvers in the proximity of the runway, which is typical of actual operations for the design of the final approach legs (arrivals) and initial climb legs (departures). 4.4.1. Heuristic function and node expansion scheme selection

如图 4 所示，对于给定的飞机位置，可以根据用于后继操作符的参数 (例如 $\alpha, \beta, \gamma, \delta, d, I$) 确定指示其下一个潜在位置的节点数量。这些参数依赖于飞机的类型，并通过相应的爬升和下降率来表达，这些率可以在飞机数据库 (BADA)(Nuic，2010 年) 中找到。此外，飞机性能会根据 (1) 高度/速度和 (2) 操作类型 (例如，到达/起飞) 而变化。为了尽可能真实地捕捉飞机的机动性，从宏观视角 (与微观视角相对，后者使用基于质量的模型来描述飞机动力学)，开发了四种不同的后继操作符函数 (指定为 StateSpaceSearch 函数，范围从 I 到 IV，见表 1)。后继节点根据相应函数和当前父节点的状态生成。这允许例如在跑道附近进行更陡峭的水平机动，这在实际操作中对于设计最终进近段 (到达) 和初始爬升段 (起飞) 是典型的。4.4.1. 启发式函数和节点扩展方案选择

The three-dimensional path that each dynamic route follows is designed based on the following state space search scheme. Nodes are expanded by combining the state space search strategy described above with an A* cost heuristic algorithm with the objective of minimizing the total distance travelled by each dynamic route. The A* algorithm examines nodes only in the direction of interest, which, for the design of 3-D arrival and departure routes, is obtained using the 3-D Euclidean distance.

每条动态路径遵循的三维轨迹是基于以下状态空间搜索方案设计的。节点扩展是通过将上述状态空间搜索策略与一个 A* 成本启发式算法相结合，以最小化每条动态路径的总行驶距离为目标。该 A* 算法仅检查感兴趣方向上的节点，对于三维到达和出发路线的设计，这是通过使用三维欧几里得距离获得的。

The A^* routing algorithm uses two lists for storing the nodes that are generated and expanded during the state space search: the OPEN and CLOSED lists. The former stores the available nodes that are sorted in an ascending order of their evaluation function value f_i . The A* always expands the state space search starting from the top of this list (e.g. selecting the node with the lower evaluation function value). While the OPEN list only includes nodes that can be expanded, all the other nodes that have already been generated or cannot be used for expansion are stored in the CLOSED list. This list contains all the nodes that comprise the currently generated path and all other nodes that have greater evaluation function values after each expansion step are discarded.

A^* 路由算法使用两个列表来存储在状态空间搜索过程中生成和扩展的节点:OPEN 列表和 CLOSED 列表。前者存储可用的节点，并按其评估函数值 f_i 的升序排列。该 A* 总是从列表顶部开始扩展状态空间搜索 (例如，选择评估函数值较低的节点)。OPEN 列表仅包括可以扩展的节点，而所有已生成或无法用于扩展的其他节点都存储在 CLOSED 列表中。这个列表包含构成当前生成路径的所有节点，以及在每次扩展步骤后评估函数值较大的所有其他节点都被丢弃。

4.4.2. Initialization

4.4.2. 初始化

The design of the arrival and departure routes should comply with the current runway configuration. For this, the line segment that connects the initial two stages (nodes) created by the state space search scheme (Section 4.4.1) needs to be in alignment with the corresponding runway direction of movement (arrival/departure). This is achieved by providing, as input for the design of each route, these initial stages expressed via their 3-D coordinates depending on the airport the route flies to/from, its assigned runway and its type of operation. These nodes correspond to the actual location of the final approach fix for arrivals and initial climb waypoint for departures. The nodes are then expanded employing the state space search scheme proposed in Section 4.4.1.

起降路线的设计应遵守当前的跑道配置。为此，由状态空间搜索方案 (第 4.4.1 节) 创建的初始两个阶段 (节点) 之间的线段需要对齐相应跑道的运动方向 (起飞/降落)。这是通过为每条路线的设计提供输入，这些初始阶段通过它们的三维坐标来表达，取决于航线飞往/来自的机场、指定的跑道以及其操作类型。这些节点对应于实际位置的最终进近定位点 (对于到达) 和初始爬升航点 (对于起飞)。然后，使用第 4.4.1 节中提出的状态空间搜索方案扩展这些节点。

For the design of both arrival and departure routes, the state space search initiates from the runway and moves towards the TMA boundary. This direction of search is preferred to its converse due to the following:

对于起飞和降落路线的设计，状态空间搜索从跑道开始并向 TMA 边界移动。这种搜索方向优于相反方向，原因如下:

- It allows for the alignment of the routes with the runway directions.
- 它允许将路线与跑道方向对齐。
- It reduces topological complexity of the routing structure, as routes are naturally directed to their corresponding terminal waypoints, which are already distributed to the terminal boundary in accordance with the selected terminal separation standards. The benefit of this strategy becomes more evident once a few routes are designed and the available airspace for the design of new routes is effectively reduced due to the conflict-free constraints.
- 它减少了路由结构的拓扑复杂性，因为路线自然地指向它们对应的终端航点，这些航点已经根据选定的终端间隔标准分布到终端边界。一旦设计了几条路线，由于无冲突约束，可用于新路线设计的可用空域有效减少，这种策略的优势变得更加明显。
- Designing routes by initiating the search from the terminal airspace boundary toward the runways has been found to result in additional horizontal and vertical turns per route hence reducing their smoothness and leading to additional airspace complexity (based on extensive trial-and-error experiments).
- 从终端空域边界向跑道开始搜索设计路线，被发现会导致每条路线有额外的水平和垂直转向，从而降低它们的平滑性并导致额外的空域复杂性 (基于广泛的试错实验)。

We describe below the different types of constraints that have been formulated into the routing problem below.

我们下面描述了将不同类型的约束纳入路由问题以下。

4.4.3. Constraints

4.4.3. 约束

Constraints are modeled as geometric objects (i.e. location and dimension) and stored in the CLOSED list. There are two main types of constraints: (1) those imposed by the already established routes, which are expressed via the horizontal and vertical separation; and (2) external spatial constraints, which can be conceptually expressed by typical geometric objects (e.g. cylinder) and represent airspace restrictions (e.g. no-fly zones around and above tall buildings, high terrain, noise and emission sensitive areas), areas influenced by convective weather, etc. The conflict-free concept of the route design is ensured at each node expansion step by calculating the horizontal and vertical distances between the location of each examined node and the location of the already established nodes or external objects. Nodes that fail to meet the required minimal separation are invalidated. The minimum separation distance requirements can be varied according to the Required Navigation Performance (RNP) specification. In the application reported in this paper the RNP-1 standards are selected with the horizontal and vertical separation being 3NM and 1000ft , respectively. In the case of external constraints modeled by geometric shapes, e.g. a cylinder, the cylinder radius is used instead of the separation minima.

约束被建模为几何对象 (即位置和尺寸)，并存储在闭合列表中。主要有两种约束类型:(1) 由已经建立的航线施加的约束，通过水平和垂直分隔来表示；以及 (2) 外部空间约束，可以从概念上用典型的几何对象 (例如圆柱体) 表示，并代表空域限制 (例如，高大建筑物周围和上方的禁飞区、高地形、噪声和排放敏感区域)，受对流天气影响的区域等。在每一步节点扩展中，通过计算每个检查节点的位置与已建立的节点或外部对象之间的水平和垂直距离，确保了航线设计无冲突的概念。未能满足所需最小分隔要求的节点将被无效化。最小分隔距离要求可以根据所需导航性能 (RNP) 规范而变化。在本文报告的应用中，选择了 RNP-1 标准，水平和垂直分隔分别为 3NM 和 1000ft 。对于由几何形状建模的外部约束，例如圆柱体，使用圆柱体半径代替分隔最小值。

An additional operational requirement concerns with the modeling of the merge (diverge) movement towards (away from) the runway for arrivals (departures). This is enabled by excluding, from the constraint list, the first few nodes of each route in the vicinity of the runway (recall that the route design starts with the runway). The number of nodes to be excluded is user-defined, and depends on the parameters used in the state space search scheme.

另一个额外的运行要求涉及建模向着 (离开) 跑道的合并 (分离) 动作，以便到达 (出发)。这是通过从约束列表中排除跑道附近每条航线的最初几个节点来实现的 (回想一下，航线设计从跑道开始)。要排除的节点数量由用户定义，并取决于状态空间搜索方案中使用的参数。

The algorithm is further enhanced to handle situations where the state space search scheme cannot obtain valid nodes for route expansion. This could arise in bottleneck airspace where the demand from several routes exceeds the limited supply especially with stringent external constraints. In order to avoid potential route blockage, the algorithm backtracks a predefined number of nodes (selected by the user) and recommences the state space search in a horizontal direction outside the blocked area. The blocked area is modeled as a circle (see Fig. 7) and the nodes are then expanded to the direction of interest indicated by the A^* heuristic.

算法进一步改进，以处理状态空间搜索方案无法获取有效节点进行路线扩展的情况。这种情况可能出现在瓶颈空域，其中多条航路的需求数量超过了有限的供应量，尤其是在严格的外部约束下。为了避免潜在的路线阻塞，算法回溯用户预定义的节点数量，并在被阻塞区域外的水平方向上重新开始状态空间搜索。被阻塞区域被建模为一个圆形 (见图 7)，然后节点向由 A^* 启发式指示的兴趣方向扩展。

4.4.4. Termination of a single route

4.4.4. 单条航路的终止

The calculation of each dynamic route terminates when a node reaches the target terminal waypoint of the current route. This is determined by comparing the distance from the current node to the destination with a user-defined distance threshold (3 km used in this paper, again to reflect real world operations).

每条动态航路的计算在节点到达当前航路的目标终端航点时终止。这是通过比较当前节点到目的地的距离与本文中使用的用户定义距离阈值 (3 km 来确定的，再次反映现实世界的运行情况。

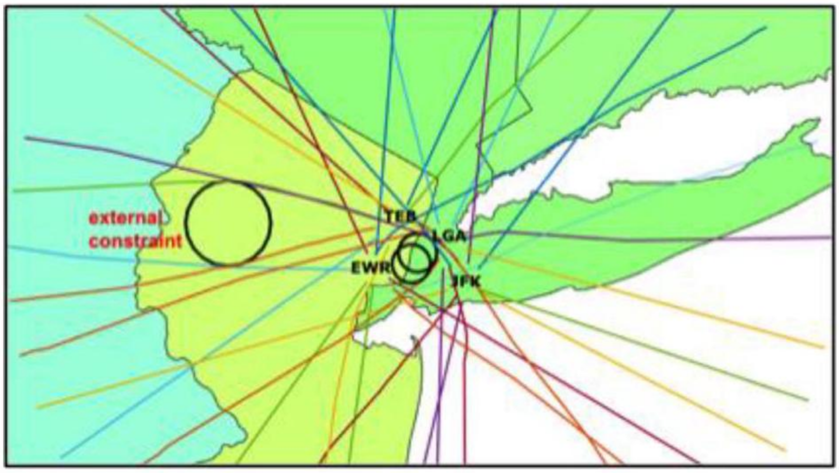

Fig. 7. Modeling external constraints (shown as the black circles).
图 7. 建模外部约束 (显示为黑色圆圈)。

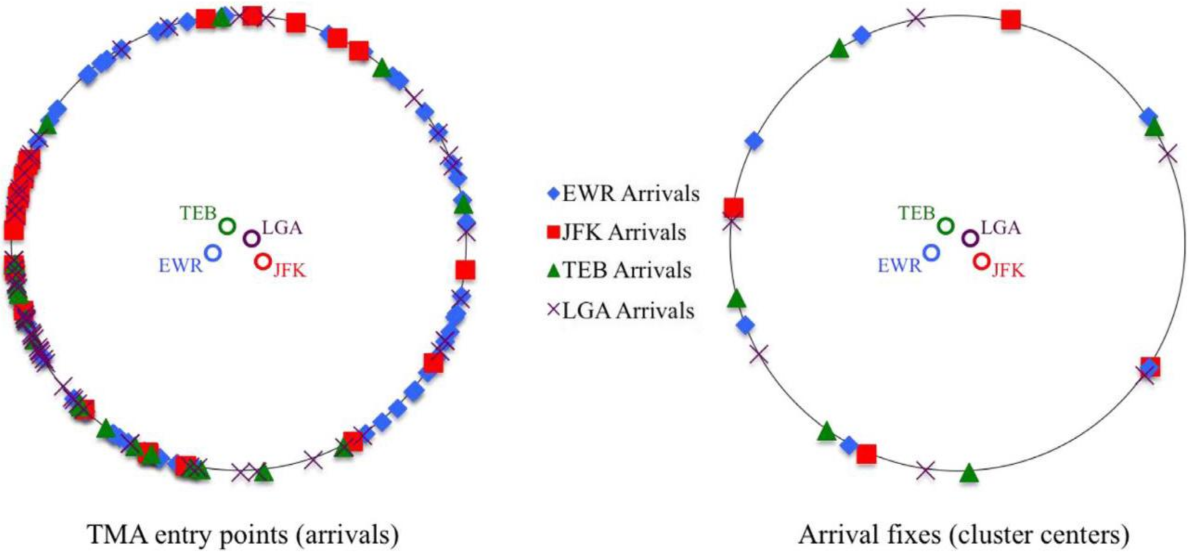

Fig. 8. Entry points (left) and their cluster centers (right) for the period 10:30-13:15.
图 8. 10:30-13:15 期间的入口点 (左) 及其聚类中心 (右)。

5.New York Metroplex case study

5. 纽约大都会区案例研究

5.1. Data description

5.1. 数据描述

The data required for the application of the framework include the scheduled (or historical) trajectories expressed as the 4-D coordinates for all flights for a given operational horizon, which can be drawn from the filed business trajectories. The data used for this NY Metroplex case study consist of aircraft trajectories during a typical day of operation in the NY TRACON in November 2011.5 The trajectories were derived from the Performance Data Analysis and Reporting System (PDARS) and were provided by the PANYNJ. The time horizon of the case study is 10:30-13:15, which is characterized by heavy air traffic demand in the study area.

应用该框架所需的数据包括预定 (或历史) 轨迹，表示为给定运行水平下所有航班的四维坐标，这些数据可以从提交的商业轨迹中获取。本研究使用的纽约大都会区案例数据包括 2011 年 11 月纽约终端雷达 Approach Control (TRACON) 典型运营日的飞机轨迹。这些轨迹来源于性能数据分析与报告系统 (PDARS)，由纽约和纽泽西港务局 (PANYNJ) 提供。案例研究的时间范围是 10:30-13:15，该时段在研究区域内呈现出繁忙的航空交通需求。

The PDARS data contain the actual aircraft trajectories, and are thus biased due to ATC actions. We pre-processed the data to remove such bias and reproduced the requested filed business trajectories. In order to do this, we assumed that all the airlines wish to fly the shortest path for any flight from their origin to their destination. The demand for an individual flight is expressed using the 4-D coordinates that mark the intersection of the great circle connecting the origin-destination pair and the small circle that represents the TMA boundary. The left hand side of Fig. 8 shows such intersections for all the arrivals during 10:30-13:15 [as per the temporal clustering described in Section 3.1; also see Sidiropoulos et al. (2017) for more details], while the right hand side shows the centers of the spatial clusters (see Section 3.2 for the details of spatial clustering).

PDARS 数据包含实际飞机轨迹，因此由于空中交通管制 (ATC) 的行动而存在偏差。我们对数据进行了预处理以去除这种偏差，并重现了请求的预定商业轨迹。为此，我们假设所有航空公司都希望飞行从起点到终点的最短路径。单个航班的需求使用 4-D 坐标表示，这些坐标标志着连接起点-终点对的大圆与表示终端区管理 (TMA) 边界的小圆的交点。图 8 的左侧显示了 10:30-13:15 期间所有到达航班的此类交

点 (如第 3.1 节中描述的时间聚类；也见 Sidiropoulos 等人 (2017 年) 的更多细节)，而右侧显示了空间聚类的中心 (详见第 3.2 节的空间聚类)。

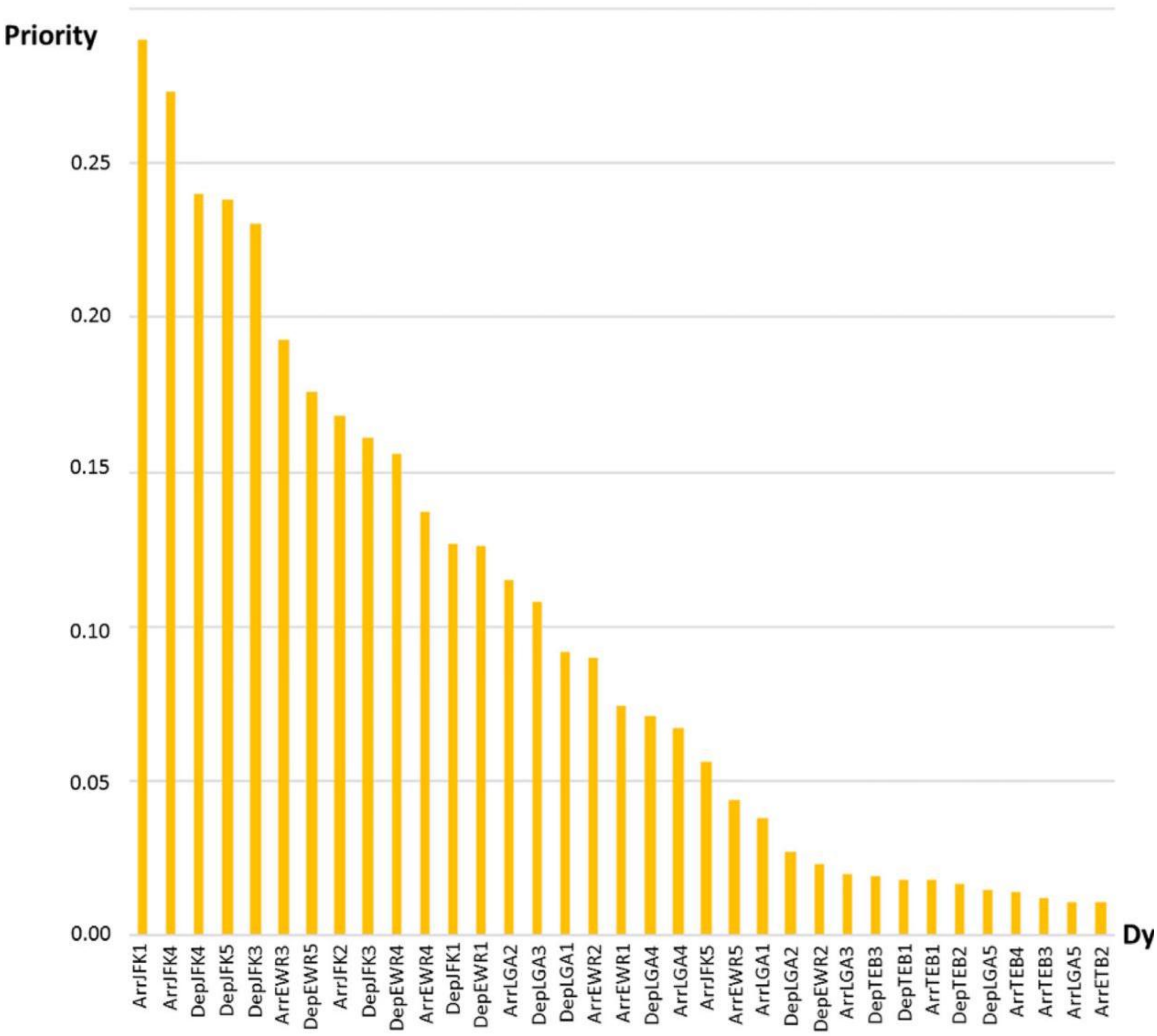

Fig. 9. Derived AHP route priorities (priorities before normalization-derived using Transparent Choice software).

图 9. 导出的层次分析法 (AHP) 路线优先级 (在归一化之前导出，使用透明选择软件)。

5.2.AHP modeling results and sensitivity analysis

5.2.AHP 建模结果和敏感性分析

The AHP model described in Section 4.2 is applied here to derive the priorities of the dynamic routes for the period 10:30-13:15. For this application, all the airports are considered of equal priority by the SMEs. The pairwise comparison assessments by the SMEs are checked for consistency with all the Consistency Ratios lower than 0.10 . The resulting priorities for the dynamic routes are presented in Fig. 9.

这里应用了第 4.2 节中描述的 AHP 模型，以导出 10:30-13:15 期间动态路线的优先级。在此应用中，所有机场都被视为具有相同的优先级。专家的成对比较评估进行了一致性检查，所有的一致性比率都低于 0.10。动态路线的优先级结果在图 9 中展示。

The priorities of the dynamic routes obtained from the proposed AHP model play a vital role in the subsequent steps leading to the 3-D route design. The quantified relative importance of a given criterion at a certain level relative to the others at the same level is determined subjectively by the SMEs using the Saaty scale (Saaty, 1990). Some common issues that may arise when using the AHP are the following (Schoner and Wedley, 1989):

由所提出层次分析法 (AHP) 模型得到的动态路线优先级在后续步骤中对于 3-D 路线设计起着至关重要的作用。在某一特定层次上，相对于同一层次上其他标准的给定标准的量化相对重要性是由 SMEs(Subject Matter Experts，主题专家) 使用 Saaty 标度 (Saaty，1990) 主观确定的。在使用 AHP 时可能出现的一些常见问题包括以下 (Schoner 和 Wedley，1989):

(1) ambiguity in the meaning of the relative importance of one criterion as compared to another; and

(1) 在比较一个标准相对于另一个标准的重要性时，其相对重要性的含义模糊；

(2) rank reversal.

(2) 排名反转。

Regarding (1), Schoner and Wedley (1989) state that "the AHP requires a specific meaning for the relative importance of criteria to yield the same answer as a direct solution". This is achieved in the referenced AHP by means of a scaling factor imposed at each level to reflect the number of the available options at the immediate lower level (Schoner and Wedley, 1989). Regarding (2), rank reversal refers to the change in the final priority order by adding/removing options. From a methodological perspective, rank reversal is eliminated when using the referenced AHP (Schoner and Wedley, 1989) if the weights change according to Eq. (9).

关于 (1)，Schoner 和 Wedley(1989) 指出，"AHP 要求相对重要性的标准具有特定含义，以便产生与直接解决方案相同的答案"。这在参考文献中的 AHP 中通过在每一层次上施加一个缩放因子来实现，该缩放因子反映了下一较低层次上可用选项的数量 (Schoner 和 Wedley，1989)。关于 (2)，排名反转指的是通过添加/删除选项而改变最终优先级顺序。从方法论的角度来看，如果在参考文献中的 AHP 中使用权重变化遵循等式 (9)，则可以消除排名反转 (Schoner 和 Wedley，1989)。

However, rank reversal may also occur when the SMEs' pairwise comparisons (higher level criteria) or absolute measurement inputs (lower level criteria) are varied. This needs to be thoroughly understood by conducting sensitivity analysis with respect to the variation of the input. There are several methods for sensitivity analysis of the AHP-derived priorities (Ishizaka and Lusti, 2006; Leonelli, 2012), with the most popular being numerical incremental analysis [others include probabilistic simulations and mathematical modeling (Leonelli, 2012)], in which the weights are perturbed to yield a new set of priorities. These perturbations are applied to one parameter at a time and the corresponding effects on the local or global priority of the alternatives are graphically illustrated.

然而，当中小企业 (SMEs) 的两两比较 (较高层次标准) 或绝对测量输入 (较低层次标准) 发生变化时，也可能发生排名反转。这需要通过对输入变化的敏感性分析进行彻底理解。有几种方法用于分析层次分析法 (AHP) 导出的优先级的敏感性 (Ishizaka 和 Lusti，2006；Leonelli，2012)，其中最流行的是数值增量分析 [其他包括概率模拟和数学建模 (Leonelli，2012)]，在这种分析中，权重被扰动以产生新的优先级集合。这些扰动一次应用于一个参数，相应的对替代方案的局部或全局优先级的影响以图形方式展示。

To ensure that the solution is well-defined and robust, numerical sensitivity analysis of the referenced AHP was conducted. This was done in this study by using Transparent Choice (Transparent Choice, 2016) for all the examined criteria. Fig. 10 presents one instance of the sensitivity analysis for the EWR dynamic routes when the weight of heavy A/C type is perturbed. The vertical red line indicates the current criterion selection (34%) and the sloped lines indicate how the global priorities of the relevant dynamic routes may be varied with such weight. In this figure, for a rank reversal to occur, the weight should be increased to approximately 68% .

为了确保解决方案是明确定义且健壮的，对参考的 AHP 进行了数值敏感性分析。在本研究中，通过使用透明选择软件 (Transparent Choice，2016) 对所有检查的标准进行了这一分析。图 10 展示了当重型 A/C 类型的权重被扰动时，EWR 动态路线敏感性分析的一个实例。垂直红线表示当前标准选择 (34%)，斜线表示相关动态路线的全局优先级如何随着这种权重变化。在这个图中，要发生排名反转，权重应增加到大约 68% 。

It is of crucial importance to identify the circumstances that might cause rank reversal. There are two sources of uncertainty. The first is an error in the judgment of the decision maker during the pairwise comparison process. This can be readily accounted for by means of the consistency assessment outlined in Section 4.2. The second source of uncertainty is the variability of the quantitative information regarding the various demand characteristics at the lower level of the hierarchy, which can be due to uncertainty in the realization of demand. Such uncertainty can be addressed by the distributionally robust optimization (DRO) approach proposed in Sidiropoulos et al. (2017). Furthermore, since such uncertainty affects only the lower-level elements, it has little impact on the overall priority, which is primarily determined by the weight derived by the pairwise comparisons. Thus, testing the pairwise comparisons for consistency using the consistency index, along with the DRO framework for deriving the dynamic routes can enhance the

robustness of the final dynamic route priorities.
识别可能导致排名逆转的情况至关重要。不确定性的来源有两个。第一个来源是决策者在成对比较过程中判断的错误，这可以通过第 4.2 节中概述的一致性评估方法轻易地加以考虑。第二个来源是关于层次结构较低层次的各种需求特征的定量信息的变异性，这可能是因为需求实现的不确定性。这种不确定性可以通过 Sidiropoulos 等人 (2017 年) 提出的分布鲁棒优化 (DRO) 方法来解决。此外，由于这种不确定性仅影响低层次元素，因此对整体优先级的影响很小，整体优先级主要是由成对比较得出的权重确定的。因此，使用一致性指数测试成对比较的一致性，并结合 DRO 框架推导动态路线，可以增强最终动态路线优先级的鲁棒性。

From Fig. 9 it is evident that a rank reversal between a highly ranked alternative (e.g. ARRJFK1) and one which is lower-ranked (ARRTEB2) is highly unlikely. The routes that may be subject to a local rank reversal are those lower-ranked (e.g. AR-RTEB3, ARRTEB2). Whether rank reversal can occur depends, quantitatively, on the consistency of the SME inputs measured by the consistency ratio (CR); see Section 4.2. Taking CR $= 0.10$ as a benchmark, we are able to calculate the corresponding maximum changes in the route priorities using Eq. (11), which is ± 0.001 . Perturbing the priority values of all the routes shown in Fig. 9 by up to 0.001, we are able to enumerate all the scenarios of rank reversal or tie, of which there are 29 . However, we note that this is a rather pessimistic representation of the rank reversal, as the actual CR calculated from the SME inputs in our case is 0.04, which is less than the benchmark value (0.10). In fact, applying CR $= 0.04$ only yields three scenarios of rank reversal/tie. In other words, given the CR of 0.040, all possible perturbations of the route priorities yield three scenarios of rank reversal/tie, which are concerned with the last eight routes in Fig. 9. This concludes a comprehensive sensitivity analysis of the AHP.

从图 9 中可以明显看出，排名较高的备选方案 (例如 ARRJFK1) 与排名较低的方案 (ARRTEB2) 之间的排名逆转是非常不可能的。可能发生局部排名逆转的是那些排名较低的路线 (例如 AR-RTEB3, ARRTEB2)。排名逆转是否会发生，从数量上取决于 SME 输入的一致性，该一致性由一致性比率 (CR) 衡量；参见第 4.2 节。将 CR $= 0.10$ 作为基准，我们能够使用方程式 (11) ± 0.001 计算相应的路线优先级最大变化。对图 9 中所有路线的优先值进行最多 0.001 的扰动，我们能够枚举所有排名逆转或并列的场景，共有 29 种。然而，我们注意到这是对排名逆转相当悲观的表述，因为我们实际计算的案例中 SME 输入的 CR 为 0.04，这低于基准值 (0.10)。实际上，应用 CR $= 0.04$ 只产生了三种排名逆转/并列的场景。换句话说，在 CR 为 0.040 的情况下，所有可能的路线优先级扰动只产生了三种排名逆转/并列的场景，这些场景涉及图 9 中的最后八条路线。这完成了对层次分析法 (AHP) 的综合敏感性分析。

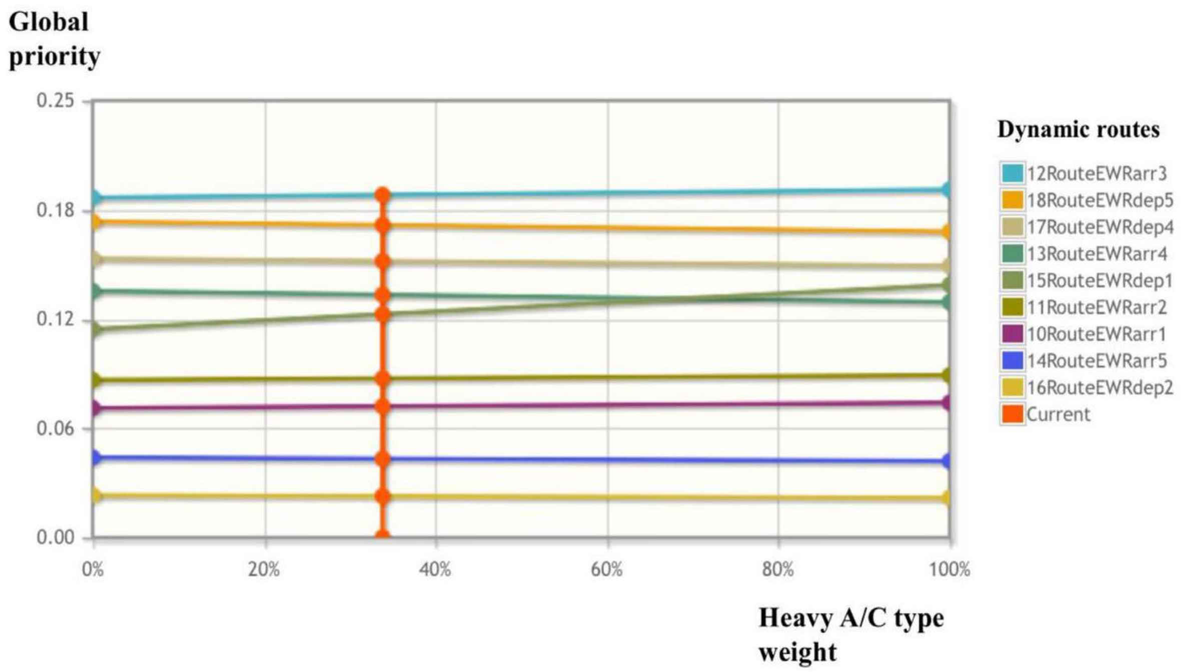

Fig. 10. Sensitivity analysis for EWR heavy A/C type criterion (derived using Transparent Choice software).
图 10. 对 EWR 重型飞机类型标准的敏感性分析 (使用 Transparent Choice 软件得出)。

In Section 5.5, we extend the sensitivity analysis to the 3-D route design by investigating how the resulting route structures are affected by the 29 instances of rank reversal. As we shall see later, such effects are negligible.

在第 5.5 节中，我们将敏感性分析扩展到三维路线设计，研究排名逆转的 29 个实例如何影响最终的路线结构。正如我们稍后会看到的，这种影响是可以忽略不计的。

5.3. Priority-based selection of terminal fixes for the NY Metroplex

5.3. 基于优先级的纽约大都会地区终端修正选择

For the selection of the terminal fixes (see Section 4.3), the minimum separation distance at the TMA boundary is $\Delta = 20$ km , which is greater than the absolute minimum required by the current standards i.e. 5NM or 9.26 km (ICAO, 2012). Normally, the optimal separation is jointly determined by the spatial configuration of the TMA and the number of dynamic routes, which in this case leads to the selected number of such fixes after several trial-and-error experiments. The additional margin between neighboring terminal fixes leads to a better initial distribution of the dynamic routes and results in fewer conflicts in 3-D routing. Fig. 11 presents the result of the priority-based terminal fix selection model

对于终端修正点的选择 (见第 4.3 节)，在 TMA 边界处的最小间隔距离为 $\Delta = 20$ km ，这大于当前标准所要求的绝对最小值，即 5NM 或 9.26 km (国际民航组织，2012 年)。通常，最佳间隔是由 TMA 的空间配置和动态路线的数量共同决定的，在这种情况下，经过多次试错实验后，导致了所选终端修正点的数量。相邻终端修正点之间的额外间隔使得动态路线的初始分布更佳，从而在三维路由中减少了冲突。图 11 展示了基于优先级的终端修正点选择模型的结果。### 5.4. Three-dimensional routing results

5.4. Three-dimensional routing results

5.4. 三维路由结果 Fig. 12 illustrates the dynamic routes for the NY Metroplex airports (JFK, EWR, LGA, TEB) obtained from the 3-D routing scheme. It can be observed that most dynamic routes follow close-to-straight curves with little turning. In addition, two external constraints were added for this particular application to account for the no-fly zones around the World Trade Center and the Empire State Building. The no-fly zones are approximated as two cylinders centered at each site with a radius of [latex0] and altitude of 3000 ft. The no-fly zones are indicated by the two black circles in the center of Fig. 12(a) and by the dark-blue cylinders in Fig. 12(b).

Fig. 12 illustrates the dynamic routes for the NY Metroplex airports (JFK, EWR, LGA, TEB) obtained from the 3-D routing scheme. It can be observed that most dynamic routes follow close-to-straight curves with little turning. In addition, two external constraints were added for this particular application to account for the no-fly zones around the World Trade Center and the Empire State Building. The no-fly zones are approximated as two cylinders centered at each site with a radius of 2.5NM and altitude of 3000 ft. The no-fly zones are indicated by the two black circles in the center of Fig. 12(a) and by the dark-blue cylinders in Fig. 12(b).

图 12 展示了从三维路由方案获得的纽约大都会机场 (JFK、EWR、LGA、TEB) 的动态路线。可以看出，大多数动态路线几乎呈直线状，转弯很少。此外，为了考虑世贸中心和帝国大厦周围的禁飞区，为本特定应用增加了两个外部约束。禁飞区被近似为以每个地点为中心、半径为 2.5NM 、高度为 3000 英尺的两个圆柱体。禁飞区在图 12(a) 中心的两个黑圈和图 12(b) 中的深蓝色圆柱体中表示。Fig. 11. Initial unimpeded terminal fixes (left) and final terminal fixes (right) for the period 10:30-13:15.

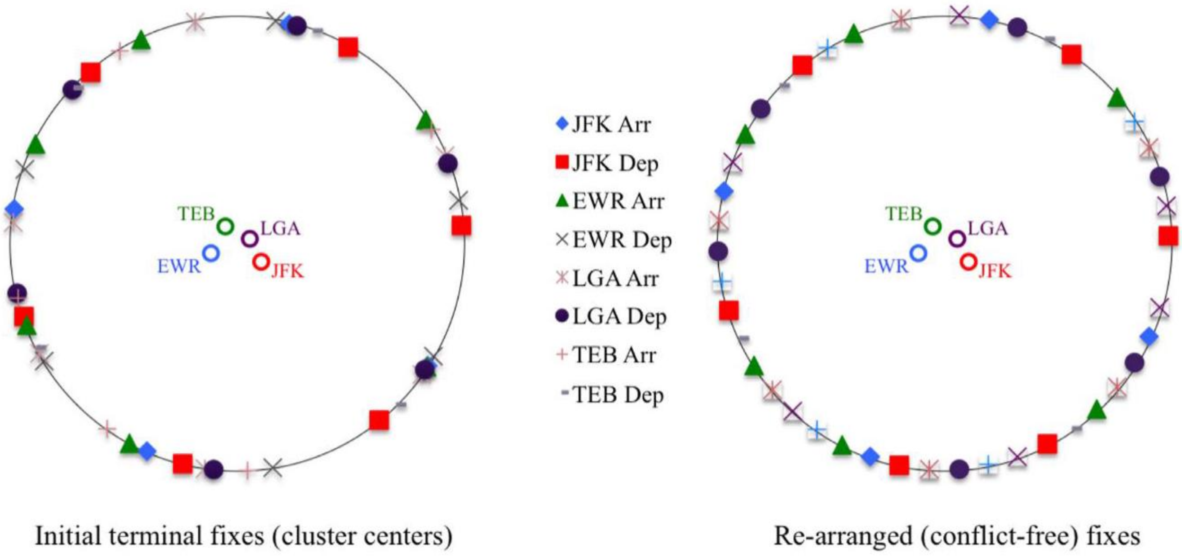

Fig. 11. Initial unimpeded terminal fixes (left) and final terminal fixes (right) for the period 10:30-13:15.

图 11。10:30-13:15 时段的初始无障碍终端修正点 (左) 和最终终端修正点 (右)。Fig. 12. (a) Plane-view of resulting route structure for period 10:30-13:15. (b) 3-D view of resulting route structure for period 10:30-13:15 (the altitudes are exaggerated by 100 times).

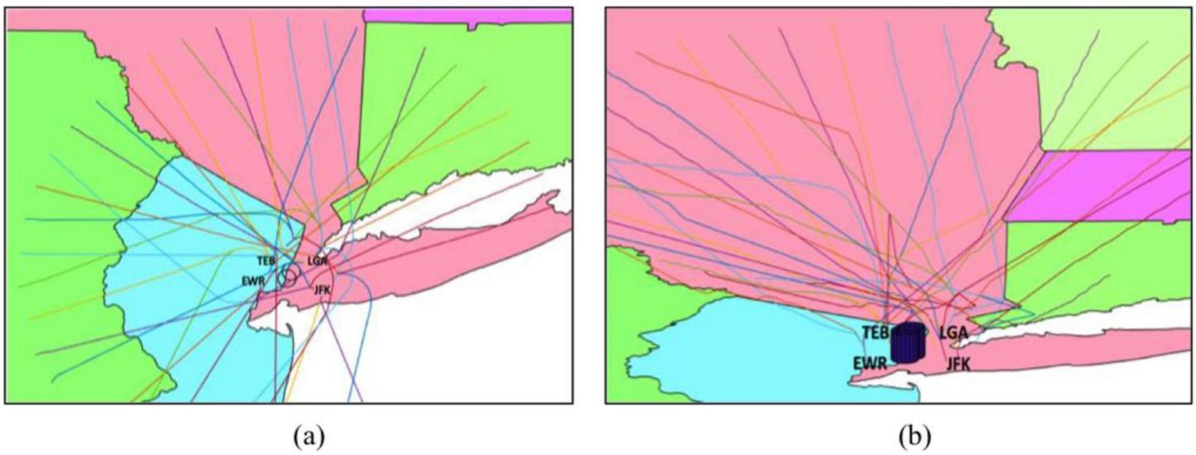

Fig. 12. (a) Plane-view of resulting route structure for period 10:30-13:15. (b) 3-D view of resulting route structure for period 10:30-13:15 (the altitudes are exaggerated by 100 times).

图 12。(a)10:30-13:15 时段的路线结构平面图。(b)10:30-13:15 时段的路线结构三维图 (高度被放大了 100 倍)。

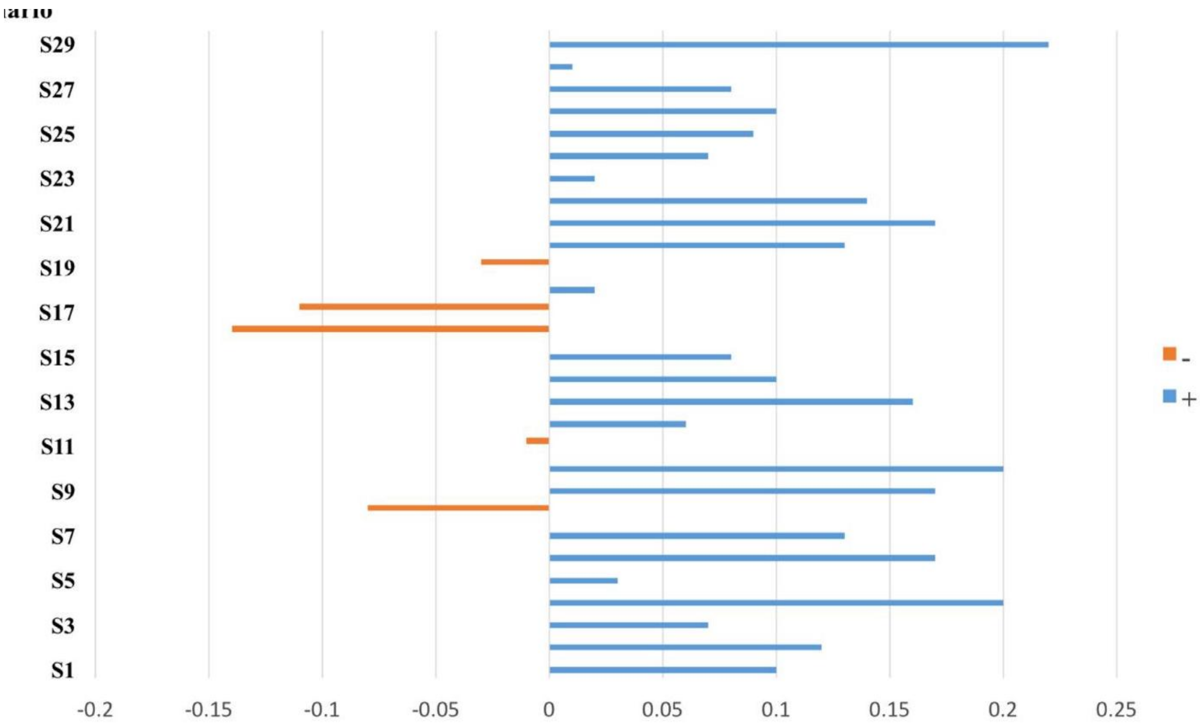

Fig. 13. The 29 scenarios of rank reversal identified from the sensitivity analysis, and the corresponding changes (in percentage) in the total distance travelled by all the flights compared to the base scenario.

图 13. 从敏感性分析中识别出的 29 个排名反转场景，以及与基准场景相比所有航班总飞行距离的相应变化 (百分比)。

5.5. Sensitivity analysis of the routing solutions

5.5. 路由解决方案的敏感性分析

From a practical point of view, it is desirable to ensure that the 3-D routing result is robust against potential rank reversal in the dynamic routes, which is caused by reasonable perturbations in the AHP-related parameters. This section fulfills this purpose.

从实际角度来看，希望确保三维路由结果对于动态路由中潜在的排名反转具有鲁棒性，这种反转是由 AHP 相关参数的合理扰动引起的。本节旨在实现这一目标。

As mentioned in Section 5.2, the priority order, which effectively acts as an input variable to calculate the routing structure, is robust with very limited rank reversal as allowed for by the consistency ratio (CR). To further analyze the sensitivity of the routing structures, we follow a similar approach in Section 5.2 by taking the benchmark CR (0.10) and the CR from our case study (0.04). For $\mathrm{CR}=0.10$, we enumerate all the 29 instances of rank reversal or tie; for $\mathrm{CR}=0.04$, we enumerate all the 3 instances of rank reversal or tie. We then calculate the corresponding route structures through the 3-D route design framework.

如第 5.2 节所述，优先顺序实际上作为计算路由结构的输入变量，其鲁棒性在一致性比率 (CR) 允许的范围内，具有非常有限的排名反转。为了进一步分析路由结构的敏感性，我们采用第 5.2 节中类似的方法，使用基准 CR(0.10) 和我们案例研究的 CR(0.04)。对于 $\mathrm{CR}=0.10$ ，我们枚举所有 29 个排名反转或并列的实例；对于 $\mathrm{CR}=0.04$ ，我们枚举所有 3 个排名反转或并列的实例。然后，我们通过三维路由设计框架计算相应的路由结构。

A design KPI was selected to evaluate and compare the performance of the 29 different routing structures. This was chosen to be the total distance travelled by all the flights on their corresponding dynamic routes, as it not only corresponds to the original multi-objective optimization problem (5), but is also a direct indicator of route efficiency in the TMA. The tornado graph in Fig. 13 illustrates the relative difference (in percentage) in the design KPIs for all the 29 scenarios when $\mathrm{CR}=0.10$, and all the 3 scenarios(S5, S11, S18)when $\mathrm{CR}=0.04$. It can be seen that the maximum variations in the KPI are approximately 0.22% (CR = 0.10) and 0.03% (CR = 0.04) , which are negligible. Fig. 14 presents the three new routing structures resulting from rank reversal/tie for CR = 0.04 . It is shown that the changes in the route structure are minor and are concerned with low-ranked dynamic routes with a very few flights in the selected test period. This provides strong evidence that the routing structure is robust against perturbations in the route priorities and potential rank reversal.

选择了设计关键绩效指标 (KPI) 来评估和比较 29 种不同路由结构的性能。选择的指标是所有航班在其相应动态路线上行驶的总距离，因为它不仅与原始的多目标优化问题 (5) 相对应，而且也是 TMA 中路线效率的直接指标。图 13 中的龙卷风图说明了当 CR = 0.10 时，所有 29 种场景的设计 KPI 的相对差异 (百分比)，以及当 CR = 0.04 时，所有 3 种场景 (S5、S11、S18) 的设计 KPI 的相对差异。可以看出，KPI 的最大变化约为 0.22% (CR = 0.10) 和 0.03% (CR = 0.04) ，这些变化是可以忽略不计的。图 14 展示了由排名反转/并列导致的 CR = 0.04 产生的三种新的路由结构。结果表明，路线结构的变化很小，仅涉及在选定测试期间航班数量非常少的低排名动态路线。这提供了强有力的证据，证明路由结构对路线优先级的扰动和潜在的排名反转具有鲁棒性。

5.6. Computational performance

5.6. 计算性能

In this section, we present a comprehensive evaluation of the computational performance of the proposed method. Fig. 15 illustrates the computational performance of the routing algorithm, on a Matlab platform run on a standard laptop with 16 GB RAM and a 2.7GHz Intel Core i7 processor. The figure shows the average computational time (over 100 independent runs) taken for the algorithm to solve the routing problem for a given number of dynamic routes. In addition to the number of routes, the computational performance is also dependent on the geometry of the problem, e.g. size of the TMA area, relative locations of the airports, orientation of the runways, and number of no-fly zones. Fig. 15 also shows that the computational time increases super-linearly with respect to the number of routes. This is because as more routes are included, the constraint set for solving the next route becomes increasingly stringent and complex, which requires more computational time. Finally, given the fact that the algorithm has been tested for one of the most complex Metroplex systems in the world with satisfactory computational efficiency, the routing algorithm is suitable for implementation in other Metroplexes.

在本节中，我们对所提出方法的计算性能进行了全面的评估。图 15 展示了在标准笔记本电脑上运行的 Matlab 平台中，路由算法的计算性能，该电脑配备了 16 GB 内存和 2.7GHz Intel Core i7 处理器。该图显示了算法解决给定数量动态路由问题的平均计算时间 (基于 100 次独立运行)。除了路由数量之外，计算性能还取决于问题的几何形状，例如 TMA 区域的大小、机场的相对位置、跑道的方向以及禁飞区的数量。图 15 还表明，计算时间随着路由数量的增加而超线性增长。这是因为随着包含的路由增多，解决下一条路由的约束集变得更加严格和复杂，这需要更多的计算时间。最后，考虑到该算法已经在一个世界上最复杂的 Metroplex 系统中进行了测试，并且具有满意计算效率，因此该路由算法适用于在其他 Metroplex 中进行实施。

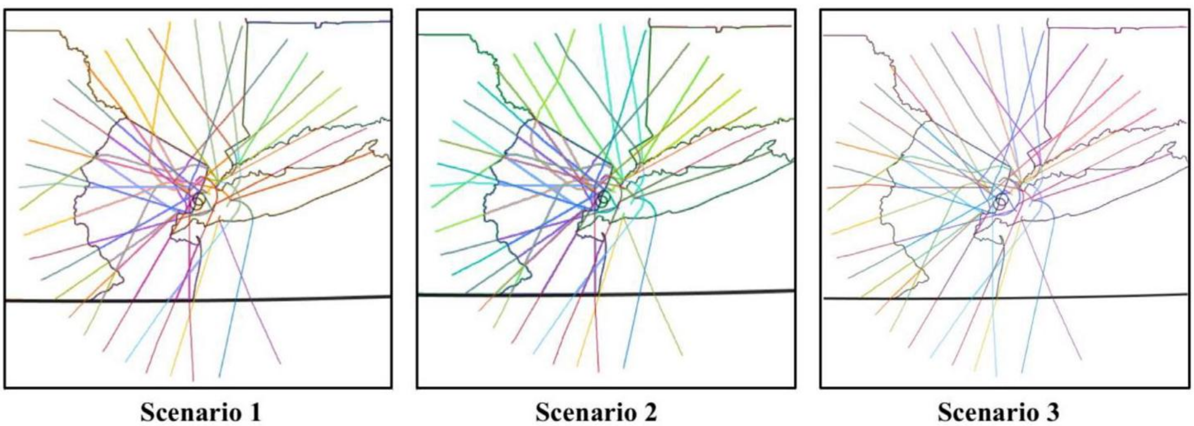

Fig. 14. The three routing structures resulting from rank reversal/tie for CR = 0.04 , based on the sensitivity analysis.

图 14。基于敏感性分析，由于排名反转/并列导致的 CR = 0.04 三种路由结构。

The proposed framework, including demand characterization, dynamic route prioritization and 3-D route design, is suitable for decision making at a pre-tactical (24 hours in advance) and operational level ($2-3$ h in advance). The input of the framework includes static information (e.g. TMA geometry, external constraints) and dynamic information (e.g. air traffic demand). Given the traffic demand, the subsequent demand characterization (i.e. S-T clustering) and route prioritization (i.e. AHP) can be easily performed with negligible computational time. The 3-D route design takes approximately 11 minutes in our case study. This makes the proposed framework entirely feasible on a pre-tactical decision-making level, where traffic demand data (forecast) are collected at the end of the day for the operation in the next 24-h horizon. It can also enable near real-time operation on a rolling horizon basis, where air traffic demand forecast with $2-3$ h look-ahead-time can be used to implement the route design, which is performed at the beginning of each time epoch (with a length of 2-3 h). The feasibility and efficacy of the rolling horizon approach is fully demonstrated in Sidiropoulos et al. (2017).

提出的框架，包括需求特征化、动态路由优先级确定和 3D 路由设计，适用于战术前 (提前 24 小时) 和操作级别的决策 ($2-3$ h 。框架的输入包括静态信息 (例如，终端区几何形状、外部约束) 和动态信息 (例如，空中交通需求)。在给定交通需求的情况下，随后的需求特征化 (即 S-T 聚类) 和路由优先级确定 (即层次分析法) 可以轻易完成，且计算时间可以忽略不计。在我们的案例研究中，3D 路由设计大约需要 11 分钟。这使得所提出的框架完全适用于战术前决策级别，其中交通需求数据 (预测) 是在当天结束时收集的，用于下一个 24 小时时间范围内的操作。它还可以实现基于滚动时间框架的近实时操作，其中可以采用 $2-3$ h 预测时间的空中交通需求预测来实施路由设计，该设计在每个时间周期 (长度为 2-3 小时) 的开始时执行。滚动时间框架方法的可行性和有效性在 Sidiropoulos 等人 (2017 年) 的研究中得到了充分证明。

Time (sec, avg over 100 runs) No. of routes

时间 (秒，100 次运行的平均值) 路由数量

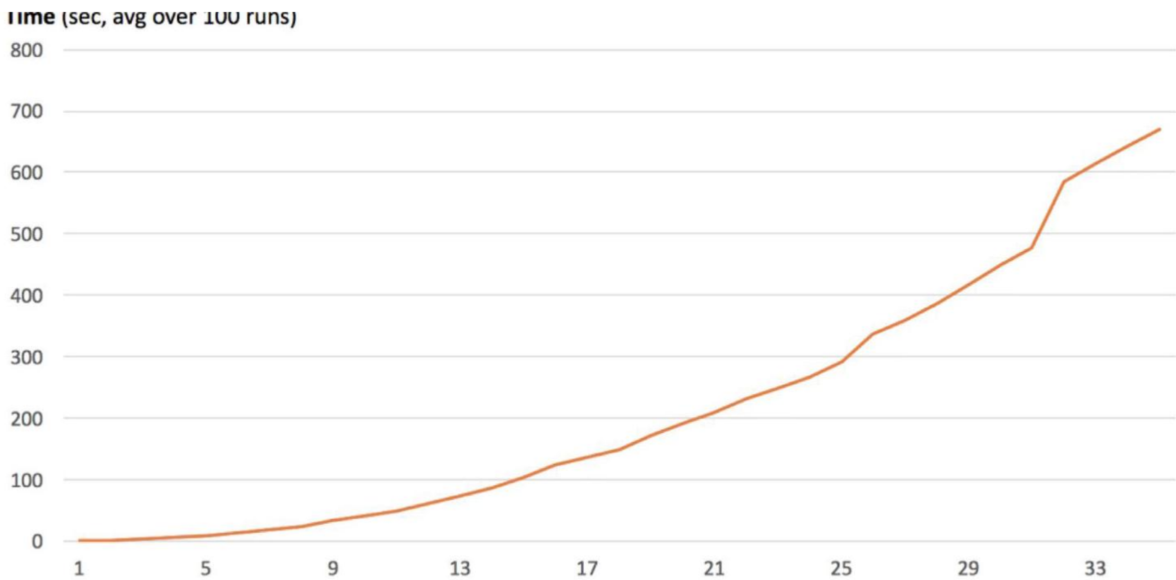

Fig. 15. Computational performance of TMA router as a function of the number of routes solved over time (s). The displayed data represent average solution times over 100 runs of the algorithm.

图 15. TMA 路由器计算性能随时间 (秒) 解决的路由数量变化。显示的数据代表了算法 100 次运行的解决方案的平均时间。

6. Simulation validation

6. 仿真验证

Fast time simulation represents an essential aspect of any attempt to assess the impacts of airspace changes in a systematic manner (Majumdar et al., 2005). AirTOp, a fast time simulation model (AirTOp Soft S.A., 2016), is used to validate the resulting design from the proposed method. The main objective of the simulation experiment is to compare the performances of the system under the new operational scenario designed by our method, in contrast to the baseline of the current operational scenario. In particular, the routing results for the period 10:30-13:15 presented in Section 5.4 are compared with the actual routing results for the same set of flights, as depicted in the PDARS data.

快速时间模拟是评估空域变化影响的任何系统尝试的基本方面 (Majumdar 等人，2005 年)。AirTOp 是一种快速时间模拟模型 (AirTOp Soft S.A.，2016 年)，用于验证所提出方法得到的设计结果。模拟实验的主要目标是对比在新操作场景下系统的性能，该场景由我们的方法设计，与当前操作场景的基线进行对比。特别是，第 5.4 节中呈现的 10:30-13:15 期间的航线结果与 PDARS 数据中同一航班集合的实际航线结果进行了比较。

6.1. Current scenario

6.1. 当前场景

In order to develop the current scenario, an existing model for the NY Metroplex (produced by AirTOp) is used as the baseline model and adjusted to cover the major features of the current operations. This was done through extensive consultation with the SMEs from the PANYNJ (ex NY TRACON air traffic controllers and airspace planners) and incorporation of information from the Aeronautical Information Publication (AIP) of the four main Metroplex airports. Such information includes:

为了开发当前场景，使用了现有的纽约大都会区模型 (由 AirTOp 制作) 作为基线模型，并进行了调整以涵盖当前操作的主要特征。这是通过与 PANYNJ(前纽约 TRACON 空中交通管制员和空域规划师) 的 SMEs 进行广泛咨询，并纳入四个主要大都会机场的航空信息出版物 (AIP) 中的信息来完成的。这些信息包括:

- Airspace: location of fixes; Standard Instrument Departure Routes (SIDs)/Standard Instrument Arrival Routes (STARs); holding patterns; vectoring areas for arrivals; horizontal separation standards (3 NM); and vertical separation standards (1000 ft)

- 空域: 定位点位置；标准仪表离港航线 (SIDs)/标准仪表进港航线 (STARs)；等待航线；进港矢量区域；水平间隔标准 (3 海里)；以及垂直间隔标准 (1000 英尺)

- Airport: runway orientations; runway geometric characteristics; runway dependencies (between the same runway or dependent runways of the same or neighboring airports); use of an operational arrival gap between dependent runways (to allow for departures to take-off between arrivals); and separation standards for take-off (based on wake turbulence category).

- 机场: 跑道方向；跑道几何特性；跑道依赖性 (相同跑道或相邻机场的依赖跑道之间)；在依赖跑道之间使用操作到达间隔 (以便在到达之间允许起飞)；以及基于尾流湍流类别的起飞间隔标准。

6.2.New scenario

6.2. 新场景

The derived dynamic routes are established as standard arrival and departure routes, and the flights are assigned to their corresponding routes. While we consider the same horizontal and vertical separation standards and airport set-up as in the Current Scenario, we use no existing SIDs and STARs, holding stacks or vectoring areas from the Current Scenario. The final approach segment of each arrival route is complemented by the design of an ad-hoc vectoring area, to allow for ATC vectoring in the absence of an AMAN system. The same group of SMEs from the PANYNJ checked the geometric characteristics of such vectoring areas.

派生的动态航线被设定为标准的到达和出发航线，航班被分配到它们相应的航线上。尽管我们考虑与当前场景相同的水平垂直间隔标准以及机场设置，但我们不使用当前场景中现有的 SID 和 STAR、等待栈或矢量区域。每个到达航线的最后进近段通过设计一个特定的矢量区域来补充，以便在没有 AMAN 系统的情况下允许 ATC 进行矢量引导。来自 PANYNJ 的同一组专家审核了这些矢量区域的几何特性。

An AMAN system attempts to separate arrival traffic, and can be applied in the en-route part of the journey, or within the TMA, before the flights reach the final approach. Within the AirTOp simulation engine, a built-in AMAN system is implemented for some tests pertaining to both Current and New Scenarios. The purpose is to demonstrate the compatibility of the proposed route design and the existing

AMAN system, as well as its full potential to improve the efficiency of the TMA operation. The AMAN within the AirTop simulation has been verified in numerous studies. [6]

AMAN 系统试图分离到达流量，并且可以应用于航程的航路部分，或者在航班到达最后进近之前在 TMA 内应用。在 AirTOp 仿真引擎中，为某些与当前和新场景相关的测试实现了一个内置的 AMAN 系统。目的是为了展示所提出航线设计与现有 AMAN 系统的兼容性，以及其充分提高 TMA 运行效率的潜力。AirTop 仿真中的 AMAN 已在多项研究中得到验证。[6]

6.3. Set-up of experiments and simulation results

6.3. 实验设置和仿真结果

The same set of flights is used in the simulations of both the Current and the New Scenarios in order to compare the system performances under the same demand input. Several variations of the base simulation scenarios are tested for a more comprehensive analysis as summarized in Table 2.

在当前场景和新场景的仿真中都使用相同的航班集合，以便在相同的需求输入下比较系统性能。为了更全面的分析，对基础仿真场景的几个变体进行了测试，如表 2 所示。

Under Scenario 1, the performance of the design is tested for a TMA radius of 70 NM around the geographical Metroplex centroid. Scenario 2 adds an AMAN system to both the current and new designs. Scenarios 3 and 4 test the extended impact of the terminal area design for a radius of 150NM and 200NM , respectively, for both the current and new designs; comparison with the reference PDARs data is also available. The reference data are not derived from the computer simulation but instead based on the empirical data relevant to the current operations. Finally, under Scenarios 5, 6 and 7, an increased demand profile is considered for both the current and new scenarios. The increased demand scenario is developed to test. whether the airspace design is capable of handling demand surges or future demand growth. The demand is increased as follows. The demand for each dynamic route is increased proportionally to its contribution to the overall airport demand; this is to preserve the ranking obtained from the AHP, and thus preserve the same routing solution. On each individual route, cloned flights are generated by randomly sampling from the set of existing flights, and the timing of each clone flight is derived following a normal distribution within a range of 3 minutes around the initial flight generator. The total number of cloned flights and their distribution among the different routes reflect a hypothetical future demand scenario. In addition, the cloning process on each individual route ensures that no artificial conflicts are generated during the process (cloned traffic is not generated in temporal proximity of the base traffic sample).

在场景 1 中，设计的性能在以地理 Metroplex 中心点为圆心，70 海里为半径的 TMA 区域内进行测试。场景 2 在现有和新设计中都增加了一个 AMAN 系统。场景 3 和场景 4 分别测试了终端区域设计在半径为 150NM 和 200NM 的扩展影响，适用于现有和新设计；同时也可以与参考 PDARs 数据进行比较。参考数据不是来源于计算机模拟，而是基于与当前运行相关的实证数据。最后，在场景 5、6 和 7 下，考虑了现有和新场景下的需求增长情况。增加的需求场景是为了测试空域设计是否能够应对需求激增或未来需求增长。需求的增加方式如下: 每个动态航线的需求按其对整体机场需求的贡献比例增加，这是为了保留 AHP 得到的排名，从而保留相同的路由解决方案。在每条单独的航线上，通过从现有航班集合中随机抽样生成克隆航班，每个克隆航班的起飞时间是在初始航班生成时间前后 3 分钟范围内的正态分布。克隆航班的总数及其在不同航线上的分布反映了一个假设的未来需求场景。此外，克隆过程确保在每条单独的航线上不会在过程中产生人为冲突 (克隆流量不会在基础流量样本的时间附近生成)。

Table 2

表格 2

Simulation scenarios (* based on empirical data rather than simulation).

模拟场景 (* 基于实证数据而非模拟)。

Scenario	Operations under		
	Current design (a)	New design (b)	Reference data (c)
1	Current 70 NM	New 70 NM	-
2	Current 70 NM—AMAN	New 70 NM–AMAN	-
3	Current 150 NM	New 150–NM	Ref 150 NM *
4	Current 200 NM	New 200 NM	Ref 200 NM *
5	Current with increased demand	New with increased demand	-
6	Current with increased demand-AMAN	New with increased demand-AMAN	-
7	Current with increased demand	New with increased demand-AMAN	-

场景	在……下的业务		
	当前设计 (a)	新设计 (b)	参考数据 (c)
1	当前 70 海里	新 70 海里	-
2	当前 70 海里—AMAN	新 70 海里–AMAN	-
3	当前 150 纳米	新 150–纳米	参考值 150 纳米 *
4	当前 200 纳米	新 200 纳米	参考值 200 纳米 *
5	当前需求增加	新需求增加	-
6	当前需求增加-AMAN	新需求增加-AMAN	-
7	当前需求增加	新需求增加-AMAN	-

The implementation of the current and new scenarios in AirTOp is illustrated in Fig. 16. In particular, the newly designed dynamic routes in Fig. 16(a) are represented by the yellow lines, while the final approach segments for the arrivals are complemented by vectoring areas, shown in pale green. The vectoring areas are designed on the basis of the following principles:

当前和新的场景在 AirTOp 中的实施如图 16 所示。特别是，图 16(a) 中新设计的动态路由由黄色线条表示，而到达的最终进近段通过矢量区域进行补充，这些矢量区域以浅绿色显示。矢量区域是基于以下原则设计的:

- The longer side of the vectoring area follows the initial dynamic route solution;
- 矢量区域的较长边遵循初始动态路由解决方案；
- The inner side of the vectoring area follows the most direct path to the final approach fix; and
- 矢量区域的内侧遵循到达最终定位点的最直接路径；并且
- Overlapping vectoring areas should be separated by 1000ft .
- 重叠的矢量区域应由 1000ft 分隔。

Even though this study designs the vectoring areas in an ad-hoc fashion, in a more generic case, airport authorities may design them in advance and the routing solution can be calibrated to match them exactly.

尽管本研究以特定方式设计了矢量区域，在更普遍的情况下，机场管理部门可能会提前设计它们，并且路由解决方案可以调整以精确匹配。

The actual flight tracks of the new and current scenarios in the simulation are shown in Fig. 16(b) and (c), respectively. The new scenario yields a much more organized and efficient structure of the arrival and departure paths compared to the current scenario, where the effect of extensive vectoring can be easily observed by the increased spread of the simulated routes.

新场景和当前场景在模拟中的实际飞行轨迹分别显示在图 16(b) 和 (c) 中。新场景相比当前场景产生了更有组织和效率的到达和出发路径结构，其中广泛矢量化的效果可以通过模拟路由的扩展轻易观察到。

In order to further quantify the efficiency of the different route designs, the following KPIs are calculated for each scenario.

为了进一步量化不同路由设计的效率，以下关键绩效指标 (KPI) 已为每个场景计算。

(a) Total distance travelled;

(a) 总飞行距离；

(b) Total flight duration;

(b) 总飞行持续时间；

(c) Total fuel burn;

(c) 总燃油消耗；

(d) Total work duration: the total sum of the time required for a controller to resolve a single conflict event; and

(d) 总工作时间: 空中交通管制员解决单个冲突事件所需时间的总和；

(e) Total BMT delay: total delay for all the flights, measured as the difference between the actual time of arrival and the Business Management Trajectory scheduled time of arrival over specific fixes.

(e) 总 BMT 延迟: 所有航班的总延迟，计算为实际到达时间与特定修正点上的业务管理轨迹计划到达时间之间的差异。

For d), AirTOp uses the DFS (Deutsche Flugsicherung GmbH, the German ANSP) event-based model for the assessment of controller workload. Under this model, each event that requires the attention/action of a controller is assigned a time value depending on its criticality; we refer the reader to Majumdar et al.

(2005) for further details. Even though modeling controller workload is not the focus of this paper, the conflict-free concept embraced by the proposed route design is expected to lead to significant reductions on the controllers' workload, given that conflict resolution comprises the predominant part of the air traffic controller workload. This indeed is corroborated by the simulation results (see Table 3 and Table 4 for the current and increased demand scenarios, respectively).

对于 d)，AirTOp 使用德国空中导航服务提供商 DFS(Deutsche Flugsicherung GmbH) 的事件模型来评估管制员的工作负荷。在这个模型中，每个需要管制员注意/行动的事件根据其紧急程度分配一个时间值；我们建议读者参考 Majumdar 等人 (2005 年) 的论文以获取更多细节。尽管本文的重点不是模拟管制员的工作负荷，但所提出航线设计中采用的冲突自由概念预计将显著降低管制员的工作负荷，因为冲突解决是空中交通管制员工作负荷的主要部分。这一点确实得到了模拟结果的支持 (参见表 3 和表 4，分别对应当前和增加需求场景)。

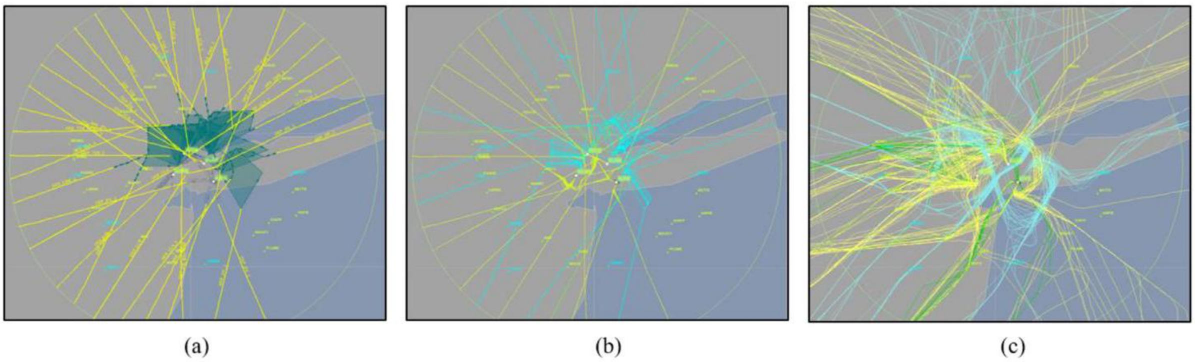

Fig. 16. Implementation of current and new designs in AirTOp. (a) Designed dynamic routes with vectoring areas. (b) Flight tracks under the new scenario (1-b in Table 2) in the simulation. (c) Flight tracks under the current scenario (1-a in Table 2) in the simulation.

图 16. 在 AirTOp 中实施当前和新的设计。(a) 设计的动态航路和向量区域。(b) 新场景下的飞行轨迹 (表 2 中的 1-b) 在模拟中。(c) 当前场景下的飞行轨迹 (表 2 中的 1-a) 在模拟中。

It can be observed from Tables 3 and 4 that the new design has superior performance compared to the current scenario, as it results in significant reductions for all the examined KPIs. When an AMAN system is applied on the arrival routes, the system performance is further improved, as the required vectoring by controllers is minimized, leading to shorter distances travelled, additional flight duration savings and lower controller workload. Overall, significant reductions are achieved for the total distance travelled, the total flight duration in the TMA, total fuel burn and total controller workload. In particular, the decrease in controllers' workload could be attributed to the fact that under the proposed concept of operations, the available airspace capacity is utilized in a more efficient manner, and is no longer strictly limited by the controller workload as at present. Finally, the comparisons between the current and new scenarios, with an extended radius of 150 NM and 200 NM, show that better management of operations within the TRACON could lead to additional improvement in the KPIs.

从表 3 和表 4 可以看出，新设计相较于当前情况具有更优的性能，因为它导致所有考察的关键绩效指标 (KPIs) 都显著降低。当在到达航路上应用空中交通管理自动化系统 (AMAN) 时，系统性能进一步提升，因为管制员所需的向量引导最小化，从而导致飞行距离缩短、额外的飞行时间节省以及管制员工作负担降低。总体而言，总飞行距离、终端区总飞行时间、总燃油消耗和总管制员工作负担都实现了显著降低。特别是，管制员工作负担的减少可以归因于在提议的运行概念下，可用空域容量以更高效的方式得到利用，且不再像目前这样严格受限于管制员的工作负担。最后，当前情况与新场景下，扩展半径为 150 海里和 200 海里的比较表明，更好地管理终端雷达服务区 (TRACON) 内的运行可能会导致关键绩效指标进一步改善。

A comparison between different TMA sizes reveals that a larger TMA implies less saving (in terms of percentage, although the absolute saving may increase as shown in Table 3). This is because most of the inefficiencies, including flight conflict and excessive controller intervention, occur within a certain range from the airport. Therefore, the proposed framework, aiming at reducing conflict and increasing operational efficiency, tends to be most effective in highly congested terminal areas, rather than for other phases of a flight (such as cruising), where fewer conflicts occur.

不同大小的终端区 (TMA) 之间的比较表明，较大的 TMA 意味着节省的百分比更小 (尽管如表格 3 所示，绝对节省可能会增加)。这是因为大多数低效现象，包括航班冲突和过度的管制员干预，都发生在

离机场一定范围内。因此，提议的框架旨在减少冲突并提高运行效率，在高度拥堵的终端区最为有效，而不是在飞行的其他阶段 (如巡航)，在这些阶段发生的冲突较少。

Nevertheless, these results should be interpreted with caution and used only as indicators for further research, as there are additional factors that characterize this airspace that are not exhaustively considered in the modeling/simulation (e.g. letters of agreement, airspace boundaries).

然而，这些结果应谨慎解读，并且仅用作进一步研究的指标，因为还有其他因素影响着该空域，而这些因素在建模/仿真中并未被彻底考虑 (例如协议信、空域边界)。

Finally, the quantification of controller workload in the fast-time simulation is based on a relatively simple metric, which is the total sum of time required to resolve a single conflict event. We note that this is not the only metric for controller workload. In the authors' opinion, a more realistic and accurate assessment of the proposed design on ATCo workload requires real-time, human-in-the-loop simulation instead of fast-time simulation. This is beyond the scope of this paper; but we are working with the PANYNJ to plan this type of experiments in the future. Even with the relatively limited and simplistic metrics of workload, the conclusion still stands that the ATCo workload can be reduced due to the much less conflict achieved by the new design. Future study will be conducted to quantify such workload reduction more accurately.

最终，快速时间模拟中控制器工作量的量化基于一个相对简单的指标，即解决单个冲突事件所需的总时间。我们注意到，这不是衡量控制器工作量的唯一指标。在作者看来，要更现实、更准确地评估所提出设计对空中交通管制员工作量的影响，需要实时、人在回路中的模拟，而不是快速时间模拟。这超出了本文的范围；但我们正在与 PANYNJ 合作，计划在未来进行这类实验。即使是在相对有限和简单的工作量指标下，结论仍然成立，即由于新设计实现的冲突大幅减少，空中交通管制员的工作量可以降低。未来的研究将对这种工作量减少进行更准确的量化。

Table 3

表 3

Comparison results in scenarios for current demand scenario (traffic sample 1), 10:30-13:15.

当前需求场景 (交通样本 1) 下的比较结果，10:30-13:15。

Scenario	Scenario description	Total distance (NM)	Total flight duration (h)	Total fuel burn (kg)	Total work duration (h)	Total BMT delay (h)
1	Current 70 NM	45,403.5	147:47:52	328,783.43	12:59:00	25:30:04
	New 70 NM	39,369.1	131:34:35	295,416.75	09:41:32	17:30:32
	(New-current) %	-13.29	-10.98	-10.15	-25.35	-31.40
2	Current 70 NM-AMAN	45,937.6	149:59:34	331,336.68	12:59:37	28:09:25
	New 70 NM-AMAN	38,961.6	132:21:11	297,300.72	09:47	20:43:58
	(New-current) %	–5.19	-11.76	-10.27	-24.71	-26.37
3 3a 3b	Current 150 NM	78,312	234:40:42	524,430.78	-	-
	New 150 NM	71,219	214:12:20	448,838.88	-	-
	(New-current) %	–9.06	-8.72	–14.41	-	-
	Ref current 150 NM	77,755.1	238:03:14	-	-	-
	New 150 NM	71,219	214:12:20	448,838.88	-	-
	(New-current) %	-8.41	-10.02	-	-	-
4 4a 4b	Current 200 NM	100,488.1	296:15:56	662,326.99	-	-
	New 200 NM	94,468.8	274:28:10	584,156.32	-	-
	(New-current) %	–5.99	–7.36	-11.80	-	-
	Ref current 200 NM	99,509.2	296:54:49	-	-	-
	New 200 NM	94,468.8	274:28:10	584,156.32		-
	(New-current) %	–5.07	–7.56	-	-	-

场景	场景描述	总距离 (海里)	总飞行时长 (小时)	总燃油消耗 (千克)	总工作时间 (小时)	总 BMT 延迟 (小时)
1	当前 70 海里	45,403.5	147:47:52	328,783.43	12:59:00	25:30:04
	新 70 海里	39,369.1	131:34:35	295,416.75	09:41:32	17:30:32
	(新-当前)%	-13.29	-10.98	-10.15	-25.35	-31.40
2	当前 70 海里-AMAN	45,937.6	149:59:34	331,336.68	12:59:37	28:09:25
	新 70 海里-AMAN	38,961.6	132:21:11	297,300.72	09:47	20:43:58
	(新-当前)%	–5.19	-11.76	-10.27	-24.71	-26.37
3 3a 3b	当前 150 纳米	78,312	234:40:42	524,430.78	-	-
	新 150 纳米	71,219	214:12:20	448,838.88	-	-
	(新-当前)%	–9.06	-8.72	–14.41	-	-
	参考当前 150 纳米	77,755.1	238:03:14	-	-	-
	新 150 纳米	71,219	214:12:20	448,838.88	-	-
	(新-当前)%	-8.41	-10.02	-	-	-
4 4a 4b	当前 200 纳米	100,488.1	296:15:56	662,326.99	-	-
	新 200 纳米	94,468.8	274:28:10	584,156.32	-	-
	(新-当前)%	–5.99	–7.36	-11.80	-	-
	参考当前 200 海里	99,509.2	296:54:49	-	-	-
	新 200 纳米	94,468.8	274:28:10	584,156.32		-
	(新-当前)%	–5.07	–7.56	-	-	-

Table 4

表 4

Comparison scenarios for increased demand (traffic sample 2), 11:00-12:30.

增加需求场景下的比较 (交通样本 2)，11:00-12:30。

Scenario	Scenario description	Total distance (NM)	Total flight duration (h)	Total fuel burn (kg)	Total work duration (h)
5	Peak current 70 NM	36,739.9	124:28:22	236,786.86	14:39:46
	Peak new 70 NM	31,669.5	111:36:34	210,684.67	10:47:23
	(New-current) %	-13.80	-10.33	-11.02	-26.41
6	Peak current 70 NM-AMAN	36,002.2	122:11:04	235,117.22	13:32:04
	Peak new 70 NM-AMAN	29,195.6	100:56:58	203,965.31	07:49:05
	(New-current) %	-18.9	-17.2	-13.25	-42.22
7	Peak current 70 NM	36,739.9	124:28:22	236,786.86	14:39:46
	Peak new 70 NM-AMAN	29,195.6	100:56:58	203,965.31	07:49:05
	(New-current) %	-20.53	-18.90	-13.86	-46.68

场景	场景描述	总距离 (海里)	总飞行时长 (小时)	总燃油消耗 (千克)	总工作时间 (小时)
5	峰值电流 70 海里	36,739.9	124:28:22	236,786.86	14:39:46
	峰值新 70 纳米	31,669.5	111:36:34	210,684.67	10:47:23
	(新-当前) %	-13.80	-10.33	-11.02	-26.41
6	峰值电流 70 纳米-AMAN	36,002.2	122:11:04	235,117.22	13:32:04
	峰值新 70 纳米-AMAN	29,195.6	100:56:58	203,965.31	07:49:05
	(新-当前) %	-18.9	-17.2	-13.25	-42.22
7	峰值电流 70 海里	36,739.9	124:28:22	236,786.86	14:39:46
	峰值新 70 纳米-AMAN	29,195.6	100:56:58	203,965.31	07:49:05
	(新-当前) %	-20.53	-18.90	-13.86	-46.68

7. Conclusions

7. 结论

As air traffic grows, MAS in the World's major cities are increasingly crucial in ensuring that such traffic can be adequately catered for without accompanying negative consequences. Yet it is in the very nature of the spatial proximity amongst the airports comprising a MAS, making their operations interdependent, to pose considerable challenges to their efficient management. In particular, the absence of any effective centralized coordination for such operations means that currently, air traffic controllers use their experience to manage traffic in such systems in an ad-hoc manner. It's no surprise therefore that the operations of such systems is far from optimal, leading to many negative consequences, e.g. poor usage of the potential capacity of the system, longer routings for aircraft.

随着航空交通的增长，世界主要城市的多机场系统 (MAS) 在确保能够充分应对这种交通需求而不伴随负面后果方面越来越重要。然而，正是构成 MAS 的机场之间的空间接近性本质，使得它们的运营相互依赖，给它们的效率管理带来了相当大的挑战。特别是，目前缺乏对这些运营有效的集中协调，意味着空中交通管制员目前只能依靠他们的经验以临时方式管理这些系统中的交通。因此，这些系统的运营远非最佳，导致了许多负面后果，例如系统潜在容量使用不足，飞机的航线更长。

Previous attempts to tackle this issue have focused on routing algorithms under the assumption that the design of the terminal airspace of the MAS is fixed. The problem with this approach is that not only does it lead to, at best, piecemeal improvements in the operations of a MAS, it also fails to take into account the major step changes proposed in air traffic management in the USA and in Europe, such as dynamic airspace configuration (DAC).

之前尝试解决这个问题的工作主要集中在假设 MAS 终端空域设计固定的情况下，研究路由算法。这种方法的问题在于，它最多只能带来 MAS 运营的零星改进，而且它还未能考虑到在美国和欧洲提出的空中交通管理中的重大步骤变化，例如动态空域配置 (DAC)。

The framework outlined in this paper not only provides a novel routing algorithm for such a MAS, it also simultaneously tackles the terminal airspace design of the MAS. In this respect it accounts for both strategic and tactical operations in a MAS, which is in stark contrast to previous research in this domain.

本文概述的框架不仅为 MAS 提供了新颖的路由算法，同时还同步解决了 MAS 的终端空域设计问题。在这方面，它同时考虑了 MAS 的战略和战术运营，这与该领域之前的研究形成了鲜明对比。

It is important to note that the key innovation made in this paper concerns with the dynamic airspace configuration and the notion of dynamic route structure; a series of methodologies are developed along the way for demand characterization, dynamic route formulation and prioritization, as well as 3-D routing within the TMA, all aimed at the ultimate goal of improving design and flow efficiencies and reducing controller workload. The number of airports involved in this process is not essential for the application of the methodology. In other words, the same framework can be equally applied to single-or two-airport systems. The only difference is that the level of congestion reduction might vary, depending on the existing static route structure and level of traffic demand. However, these quantitative differences do not diminish the scientific value and applicability of our work as a novel solution for the design of terminal airspace in general.

需要注意的是，本文的关键创新涉及动态空域配置和动态路由结构的理念；一系列方法在这个过程中被开发出来，用于需求特征化、动态路由的制定和优先级划分，以及在 TMA 内的三维路由，所有这些都是为了最终目标——提高设计和流量效率，减少管制员的工作量。在这个过程中涉及的机场数量对于该方法的应用并不是必要的。换句话说，同样的框架可以同样适用于单机场或双机场系统。唯一的区别在于，拥堵减少的水平可能会有所不同，这取决于现有的静态路由结构和交通需求水平。然而，这些数量上的差异并不会削弱我们工作作为终端空域设计新颖解决方案的科学价值和适用性。

In our current framework, including the fast-time simulation, we only consider fixed runway configurations. However, the framework is generic and can accommodate any configuration by simply altering the coordinates and runway directions for the 3-D route design. One could even consider runway configuration as an internal control variable of the integrated runway-configuration-3D-routing problem.

在我们当前的框架中，包括快速时间模拟，我们只考虑固定跑道配置。然而，该框架是通用的，可以通过简单地改变坐标和跑道方向来适应任何配置的 3D 路由设计。甚至可以将跑道配置视为集成跑道配置-3D 路由问题的内部控制变量。

While the modeling of uncertain air traffic demand is out of scope of this paper, it can be addressed with minor modifications to the proposed framework as follows. The distribution of flight delay (or error in traffic demand prediction) can be obtained from historical data. The variations in the demand can be characterized using robust clustering method (Sidiropoulos et al., 2017), which allows the traffic demand uncertainties to be factored into the TMA design, such that the proposed framework can be applied on a pre-tactical level (with a 24-h forecast) or operational level (with a 2-h forecast). Notice that the level of uncertainties in the demand depends on the scope of the prediction (i.e. pre-tactical or operational).

本文虽未涉及不确定性航空交通需求的建模，但可以通过对所提出框架的少许修改来处理。航班延误 (或交通需求预测误差) 的分布可以通过历史数据获得。需求的变化可以通过稳健的聚类方法 (Sidiropoulos 等人，2017 年) 来表征，这允许将交通需求的不确定性因素纳入 TMA 设计中，从而使所提出的框架可以应用于预先战术层面 (具有 24 小时预测) 或操作层面 (具有 2 小时预测)。需要注意的是，需求中的不确定性水平取决于预测的范围 (即预先战术或操作)。

Finally, this paper tests the proposed framework in arguably the world's most complex and busiest MAS, the New York Metroplex, by a hybrid combination of qualitative methods, i.e. the use of subject matter experts, and quantitative methods, i.e. the use of a high fidelity simulation model of the Metroplex. The results are highly promising and the implications of this are manifold. A major implication is that the framework outlined provides the basis for the design of airspace in any MAS system around the World, and thereby fulfills an objective of the ICAO. Therefore, the authors recommend the implementation of this framework by both the airport operators of a Metroplex system and by the ANSPs responsible for the design of the TMAs of single- or multi-airport systems, where the radius of the TMA boundaries should be determined case by case, to maximize the efficacy of the design.

最后，本文通过混合定性和定量方法，即利用主题专家和纽约大都会区域高保真模拟模型的使用，在世界上最为复杂和繁忙的 MAS——纽约大都会区域，对所提出的框架进行了测试。结果非常令人鼓舞，其影响是多方面的。一个重要的含义是，该框架概述了为世界任何 MAS 系统设计空域的基础，并因此满足了国际民航组织的一个目标。因此，作者建议大都会系统的机场运营商和负责设计单一或多机场系统 TMAs 的空中航行服务提供商实施这一框架，TMA 边界的半径应根据具体情况确定，以最大化设计的有效性。

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Appendix A. Details of the AHP model

附录 A. AHP 模型的详细信息

Based on Fig. 5, the route priorities are calculated as:

根据图 5，计算路线优先级如下:

$$p_i^a = f_i^a \cdot Air_i^a \cdot \begin{pmatrix} WC\left(S \cdot s_i^a + L \cdot l_i^a + H \cdot h_i^a + SH \cdot sh_i^a\right) \\ +OPS^a\left(ARR^a \cdot arr_i^a + DEP^a \cdot dep_i^a\right) \\ +OD^a\left(DOM^a \cdot dom_i^a + INT^a \cdot int_i^a\right) \\ +USER^a\left(PASS^a \cdot pass_i^a + CAR^a \cdot car_i^a\right) \end{pmatrix} \tag{11}$$

subject to:
受限于:

$$\sum_{a=1}^{A}\sum_{i=1}^{n^a} p_i^a = 1$$

where
其中
p_i^a : the priority of route i of airport a ,
p_i^a : 机场 a 的路线 i 的优先级,
WC: AHP-derived weight for the ’weight class’ attribute, normalized for the number of options of the weight class criterion within the 3rd level criteria,
WC: 基于 AHP 的’ 重量类别’ 属性权重，针对重量类别标准内的选项数量标准化,
S : AHP-derived weight for small aircraft,
S : 基于 AHP 的小型飞机权重,
s_i^a : the number of small aircraft on route i of airport a over the total number of small aircraft associated with airport a ,
s_i^a : 机场 a 路线 i 上的小型飞机数量占总小型飞机数量的比例,
AHP-derived weight for large aircraft,
基于 AHP 的大型飞机权重,
l_i^a : the number of large aircraft on route i of airport a over the total number of large aircraft associated with a ,
l_i^a : 机场 a 路线 i 上的大型飞机数量占总大型飞机数量的比例,
$\dot{H}$: AHP-derived weight for heavy aircraft,
$\dot{H}$: 基于 AHP 的重型飞机权重,
h_i^a : the number of heavy aircraft on route i of airport a over the total number of heavy aircraft associated with a ,
h_i^a : 机场 a 路线 i 上的重型飞机数量占总重型飞机数量的比例,
: AHP-derived weight for super heavy aircraft,
超重型飞机的 AHP 衍生权重,
${}_i^a$: the number of super heavy aircraft on route i of airport a over the total number of super heavy aircraft associated with a ,
${}_i^a$: 机场 a 路线 i 上的超重型飞机数量与与 a 相关联的总超重型飞机数量的比例,
PS^a : AHP-derived weight for the ’ operations type’ attribute of airport a , normalized for the number of options of the operations type criterion within the 3rd level criteria
PS^a : 机场 a 的‘运营类型’属性的 AHP 衍生权重，针对运营类型标准在 3rd 级别标准内的选项数量进行归一化,
AHP-derived weight for arrivals of airport a ,
机场 a 到达的 AHP 衍生权重,
the number of arrival aircraft on route i of airport a over the total number of arrival aircraft associated with a ,
机场 a 路线 i 上的到达飞机数量与与 a 相关联的总到达飞机数量的比例,
AHP-derived weight for departures of airport a ,
机场 a 出发的 AHP 衍生权重,
dep ${}_i^a$: the number of departure aircraft on route i of airport a over the total number of departure aircraft associated with a ,
dep ${}_i^a$: 机场 a 路线 i 上的出发飞机数量与与 a 相关联的总出发飞机数量的比例,
AHP-derived weight for origin-destination type, normalized for the number of options of the origin-destination criterion within the 3rd level criteria of airport a ,
起讫类型的 AHP 衍生权重，针对起讫标准在 3rd 级别标准内的选项数量进行归一化，机场 a ,
AHP-derived weight for domestic flights of airport a
机场 a 国内航班的 AHP 衍生权重,

^{I} : the number of domestic aircraft, over the total number of domestic aircraft

^{I} : 国内飞机数量，占总国内飞机数量的比例，

AHP-derived weight for international flights of airport a

机场 a 国际航班的 AHP 衍生权重，

int $_{i}^{a}$: the number of international aircraft, over the total number of international aircraft

int $_{i}^{a}$: 国际飞机数量，占总国际飞机数量的比例

$USER^{a}$: AHP-derived weight for the ' user type' attribute of airport a , normalized for the number of options of the user type criterion within the 3rd level criteria

$USER^{a}$: AHP 方法得出的机场“用户类型”属性的权重 a ，针对用户类型标准在 3rd 级别标准内的选项数量进行归一化

$PASS^{a}$: AHP-derived weight for passenger aircraft of airport a

$PASS^{a}$: AHP 方法得出的机场乘客飞机的权重 a

pass $_{i}^{a}$: the number of passenger aircraft, over the total number of passenger aircraft

pass $_{i}^{a}$: 乘客飞机数量，占总乘客飞机数量的比例

CAR^{a} : AHP-derived weight for cargo aircraft of airport a

CAR^{a} :AHP 方法得出的机场货运飞机的权重 a

car_{i}^{a} : the number of cargo aircraft, over the total number of cargo aircraft

car_{i}^{a} : 货运飞机数量，占总货运飞机数量的比例

The set of alternatives (dynamic routes) is located at the bottom level of the hierarchy (see Fig. 5). Since the objective of the prioritization model is to assign the priorities to each individual route, a proportionality factor $f_{i}^{a}=\frac{n_{i}^{a}}{\sum\limits_{a'\in M}\sum\limits_{j=1}^{N(a)} n_{j}^{a'}}$ needs

替代方案 (动态路线) 集合位于层次结构的底部 (见图 5)。由于优先级模型的目的是为每条单独的路线分配优先级，因此需要在第二级标准中包含一个比例因子 $f_{i}^{a}=\frac{n_{i}^{a}}{\sum\limits_{a'\in M}\sum\limits_{j=1}^{N(a)} n_{j}^{a'}}$ ，以调整每条路线的优先级，使其与每个机场的路线数量相匹配。为此，$f_{i}^{a}=\frac{n_{i}^{a}}{\sum\limits_{a'\in M}\sum\limits_{j=1}^{N(a)} n_{j}^{a'}}$ 表示路线中的航班数量 [latex1] ，[latex2] 表示往返机场的路线数量，[latex3] 表示与机场相关的路线数量，[latex4] 是 MAS 机场的集合。

to be included in the 2nd level criteria to adjust the per route priorities to be analogous to the number of routes per airport. For this, n_{i}^{a} denotes the number of flights in routes i to/from airport a, N^{a} denotes the number of routes associated with airport a , and M is the set of MAS airports.

需要包含在第二级标准中，以调整每条路线的优先级，使其与每个机场的路线数量相匹配。为此，n_{i}^{a} 表示路线中的航班数量 i ， a, N^{a} 表示往返机场的路线数量，a 表示与机场相关的路线数量，M 是 MAS 机场的集合。

Appendix B. Details of the SME inputs to the AHP model

附录 B. AHP 模型中 SME 输入的详细信息

The hierarchy structured in this model is developed based on the literature on airport and MAS operations; and the subsequent criteria are validated by 7 Subject Matter Experts (SMEs). Some basic information on these SMEs are:

该模型中的层次结构是基于机场和 MAS 运营的文献开发的；后续标准由 7 名主题专家 (SMEs) 验证。这些 SME 的一些基本信息如下:

1. Program manager PANYNJ, ex-TRACON controller, computer science background with over 30 years of experience

1. PANYNJ 项目经理，前 TRACON 控制器，计算机科学背景，拥有超过 30 年的经验

2. Director of aviation environment and sustainability, aviation regional planning supervisor, PANYNJ, over 30 years of experience

2. 航空环境与可持续发展主管，航空区域规划监督员，PANYNJ，拥有超过 30 年的经验

3. Senior airport planner, over 10 years of experience, PANYNJ

3. 高级机场规划师，拥有超过 10 年的经验，PANYNJ

4. Director at PANYNJ aviation department, manager of operations at EWR airport, over 30 years of experience

4. PANYNJ 航空部门主管，EWR 机场运营经理，拥有超过 30 年的经验

5. JFK, EWR, LGA, TEB tower managers, over 30 years of experience

5. JFK、EWR、LGA、TEB 塔台经理，拥有超过 30 年的经验
6. Managing director United Airlines with over 30 years of experience.
6. 联合航空公司管理董事，拥有超过 30 年的经验。

Regarding the formulation of the AHP model: the SMEs were first interviewed individually or in small groups to assess the AHP structure. The model structure was revised to capture adequately the current state of affairs based on their assessments. This procedure was iterated until they unanimously agreed on the final AHP model structure presented here.

关于 AHP 模型的构建: 首先单独或以小组形式对 SMEs 进行访谈，以评估 AHP 结构。根据他们的评估，模型结构被修订，以充分捕捉当前事务的状态。此过程经过多次迭代，直到他们对这里呈现的最终 AHP 模型结构达成一致意见。

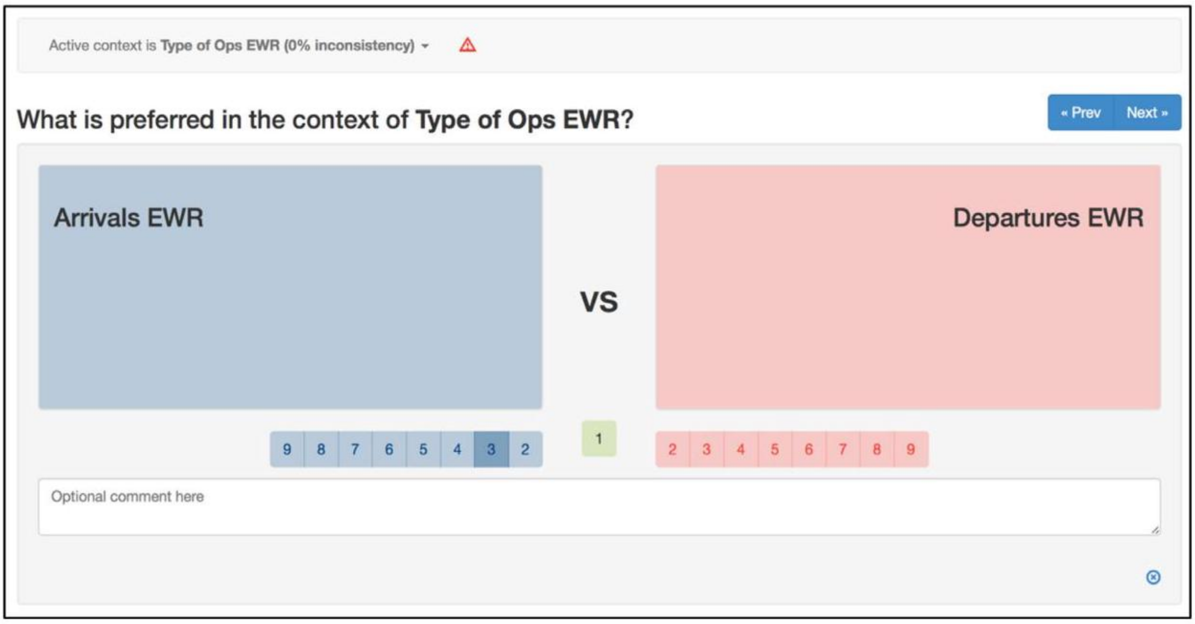

Fig. 17. SME pairwise comparison for EWR type of operation criterion, Transparent Choice software.

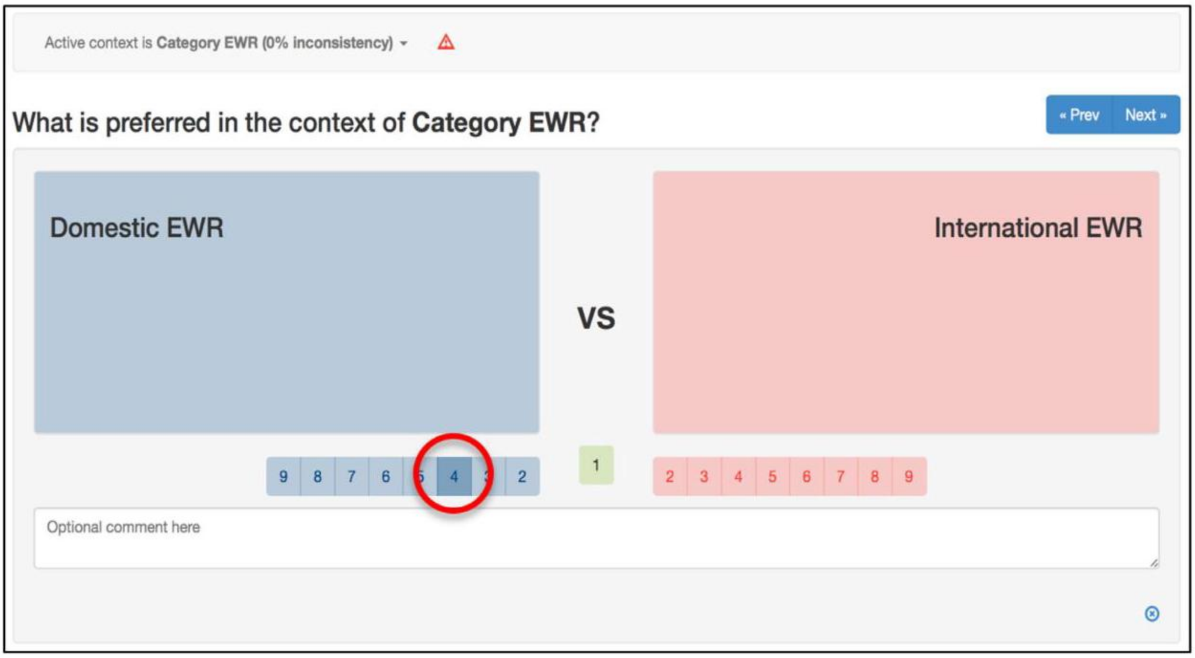

Fig. 18. SME pairwise comparison for EWR category criterion, Transparent Choice software.

The validation of the AHP model was done by one SME, in the role of the TRACON manager. In general, the AHP model is formulated by combining the interests of the different stakeholders (airports) in terms of their preferred management strategies. The AHP structure based on the experience of the SMEs presents an objective assessment of the relative importance of each criterion. When it comes to the actual validation, the dominating factor that influences the priorities is air traffic demand. The management strategies of each airport are accounted for in this assessment. For example, both JFK and EWR are operating with a departure push strategy in the period 08:00-10:00, while the arrival/departure ratio for LGA and TEB would be 50/50 for this period. This information is known to the SMEs from a given Metroplex, and is directly derived by the demand data (in particular the arrival/departure slot allocation). Thus, it would not make any difference to have more than one SME for the purpose of validation. Two examples of the AHP pairwise comparisons as conducted in Transparent Choice software are illustrated in Figs. 17 and 18.

AHP 模型的验证由一位 Subject Matter Expert(SME) 执行，其担任 TRACON 经理的角色。总的来说，AHP 模型是通过结合不同利益相关者 (机场) 的偏好管理策略来制定的。基于 SME 经验的 AHP 结构，对每个标准的相对重要性提供了一个客观评估。在实际情况的验证中，影响优先级的主导因素是空中交通需求。每个机场的管理策略都在此评估中被考虑。例如，JFK 和 EWR 在 08:00-10:00 期间都采用出发推动策略，而 LGA 和 TEB 的到达/出发比例在此期间为 50/50。SMEs 从给定的 Metroplex 中了解到这一信息，并且直接由需求数据 (尤其是到达/出发时间槽的分配) 得出。因此，在验证目的上，拥有一个以上的 SME 并不会产生任何差异。在 Transparent Choice 软件中进行的 AHP 成对比较的两个示例在图 17 和图 18 中说明。

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