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ANALYSIS OF THE ISSUES OF MODELING THE AIR TRAFFIC CONTROL PROCESS WITH INCREASING FLIGHT INTENSITY

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Abstract. *The air traffic control (ATC) process is a complex and dynamic system that ensures the safe and efficient operation of aircraft in the airspace. The ATC process involves various actors, such as pilots, controllers, airports, airlines and regulators, who communicate and coordinate their actions through various systems and procedures. The ATC process is influenced by many factors, such as weather, traffic, technical conditions, human factors and others. The ATC process is also subject to changes and uncertainties, such as increasing demand for air travel, technological innovations, environmental regulations and security threats.*

The main contribution of this article is to provide a comprehensive and integrated approach for modeling the ATC process with an increase in the intensity of flights. The article demonstrates the applicability and usefulness of the proposed models for supporting decision-making and policy making in the field of air traffic management. The article also identifies the challenges and limitations of the current ATC process and suggests directions for future research and development.

Key words: *Air traffic, air traffic control, aircraft, flow, runway, taxiway, efficiency, network, topology, globalization, coordination.*

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PARVOZLAR INTENSIVLIGINI OSHISHI SHAROITIDA HAVODAGI HARAKATNI BOSHQARISH JARAYONINI MODELLASHTIRISH MASALALARINING TAHLILI

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Annotatsiya. *Havodagi harakatni boshqarish (HHB) jarayoni havo hududida havo kemalarining xavfsiz va samarali ishlashini ta’minlaydigan murakkab va dinamik tizimdir. HHB jarayonida uchuvchilar, dispetcherlar, aeroportlar, aviakompaniyalar va tartibga soluvchilar kabi turli subyektlar ishtirok etadi, ular turli tizimlar va protseduralar orqali o‘zaro ta’sir qiladi va muvofiqlashtiradi. HHB jarayoniga ob-havo, yo‘l harakati, texnik sharoitlar, inson omillari va boshqalar kabi ko‘plab omillar ta’sir qiladi. HHB jarayoni havo qatnovining ortishi, texnologik innovatsiyalar, atrof-muhit qoidalari va xavfsizlikga nisbatan talabning ortishi kabi o‘zgarishlar va noaniqliklarga duchor bo‘ladi.*

Mazkur maqoladan ko‘zlangan asosiy maqsad parvozlar intensivligini oshirishda HHB jarayonini modellashtirishga har tomonlama va integratsiyalashgan yondashuvni ta’minlashdan iborat. Maqolada qarorlarni qabul qilish va havodagi harakatni boshqarish siyosatini ishlab chiqishni qo‘llab-quvvatlash uchun taklif qilingan modellarning qo‘llanilishi va foydaliligi ko‘rsatilgan. Maqolada, jumladan, hozirgi HHB jarayonining muammo va cheklovlari o‘rganilgan hamda kelajakdagi tadqiqot va ishlanmalar yo‘nalishlari taklif etilgan.

Kalit so‘zlar: *havodagi harakat, havodagi harakatni boshqarish, havo kemasi, oqim, obyekt, subyekt, transport, uchish-qo‘nish yo‘lagi, harakat yo‘lagi, samaradorlik, tarmoq, topologiya, globallashuv, muvofiqlashtirish.*
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АНАЛИЗ ВОПРОСОВ МОДЕЛИРОВАНИЯ ПРОЦЕССА УПРАВЛЕНИЯ ВОЗДУШНЫМ ДВИЖЕНИЕМ ПРИ УВЕЛИЧЕНИИ ИНТЕНСИВНОСТИ ПОЛЕТОВ

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Аннотация. *Процесс управления воздушным движением (УВД) представляет собой сложную и динамичную систему, обеспечивающую безопасную и эффективную эксплуатацию воздушных судов в воздушном пространстве. В процессе УВД участвуют различные субъекты, такие как пилоты, диспетчеры, аэропорты, авиакомпании и регулирующие органы, которые взаимодействуют и координируют свои действия с помощью различных систем и процедур. На процесс УВД влияют многие факторы, такие как погода, дорожное движение, технические условия, человеческий фактор и другие. Процесс УВД также подвержен изменениям и неопределенности, таким как растущий спрос на авиаперевозки, технологические инновации, экологические нормы и угрозы безопасности.*

Основной вклад этой статьи заключается в обеспечении всестороннего и интегрированного подхода к моделированию процесса УВД при увеличении интенсивности полетов. В статье демонстрируется применимость и полезность предложенных моделей для поддержки принятия решений и выработки политики в области управления воздушным движением. В статье также определяются проблемы и ограничения текущего процесса УВД и предлагаются направления будущих исследований и разработок.

Ключевые слова: *воздушное движение, управление воздушным движением, воздушное судно, поток, объект, субъект, транспорт, взлетно-посадочная полоса, рулежная дорожка, эффективность, сеть, топология, глобализация, координация.*

Introduction

Air traffic is one of the most complex and dynamic systems in the world, involving multiple actors, such as airlines, airports, air navigation service providers (ANSPs), and regulators. The demand for air transport is constantly growing, driven by economic and social factors, such as globalization, tourism, and trade. However, the capacity of the air traffic management (ATM) system, which is responsible for ensuring the safe and efficient flow of air traffic, is limited by physical, technical, and operational constraints. Therefore, there is a need to develop and implement innovative solutions that can enhance the performance and resilience of the ATM system, especially in scenarios of high traffic intensity.

Materials and Methods

One of the possible approaches to study and improve the ATM system is to use complex network theory (CNT), which is a branch of mathematics that analyzes the structure and dynamics of networks composed of nodes and links. CNT can provide useful metrics and tools to measure and compare the properties of different networks, such as centrality, connectivity, robustness, and efficiency. CNT can also help to model and simulate the behavior and evolution of networks under various conditions and scenarios [1].

In this article, we will review some of the applications of CNT to model the process of regulating air traffic with an increase in the intensity of flights. We will focus on three main aspects: the network topology of the ATM system, the network resilience to disruptions and failures, and the network optimization for performance improvement [1, 2].

Network topology of the ATM system. The ATM system can be represented as a network of nodes and links, where nodes are entities that provide or consume air traffic services, such as airports, air traffic control (ATC) agencies, or aircraft, and links are connections that enable the exchange of information or coordination between nodes, such as flight routes, radio frequencies, or data links. The network topology of the ATM system reflects its structure and organization, as well as its operational characteristics and constraints.

One example of applying CNT to analyze the network topology of the ATM system is the work by Zanin A.L. (2013), who studied the European ATM network using data from EUROCONTROL. They constructed a network where nodes were airports and links were flights between them. They calculated various network metrics, such as degree distribution, clustering coefficient, average path length, and assortativity coefficient. They found that the European ATM network had a scale-free structure, meaning that it followed a power-law degree distribution, where a few nodes had a very high number of connections (hubs), while most nodes had a low number of connections. They also found that the network had a high clustering coefficient, meaning that nodes tended to form groups or communities with dense connections among them. Moreover, they found that the network had a low average path length, meaning that a small number of hops or intermediate nodes could reach any two nodes. Finally, they found that the network had a negative assortativity coefficient, meaning that nodes tended to connect with nodes that had a different degree than them [2, 3].

The analysis of the network topology of the ATM system can provide insights into its functionality and efficiency. For instance, hubs can facilitate the connectivity and accessibility of the network, but they can also create congestion and delays. Communities can reflect regional or operational similarities or differences among nodes, but they can also create fragmentation or isolation. Path length can indicate the speed and reliability of information or coordination flows in the network, but it can also depend on external factors such as weather or regulations. Assortativity can indicate the diversity or homogeneity of node interactions in the network, but it can also affect its robustness or vulnerability [3].

Network resilience to disruptions and failures. The ATM system is subject to various types of disruptions and failures that can affect its normal operation and performance. These can be caused by natural phenomena (such as storms or volcanic eruptions), technical malfunctions (such as equipment breakdowns or cyberattacks), human errors (such as miscommunication or miscoordination), or intentional actions (such as strikes or terrorism). Disruptions and failures can have different impacts on different parts of the network depending on their severity, location, duration, frequency, and propagation.

One example of applying CNT to assess the network resilience to disruptions and failures is the work by Wang et al. (2016), who studied the Chinese ATM network using data from CAAC. They constructed a network where nodes were ATC agencies and links were flight routes between them. They simulated two types of attacks on the network: random failures, where nodes were removed randomly from the network; and targeted attacks, where nodes were removed according to their centrality measures (such as degree centrality or betweenness centrality). They measured the impact of these attacks on the network using metrics such as size of giant component (the largest connected subnetwork), average path length (the average number of hops between any two nodes), efficiency (the inverse of average path length), diameter (the maximum number of hops between any two nodes), and robustness (the ratio of size of giant component before and after the attack) [4].

They found that the Chinese ATM network was resilient to random failures, meaning that it could maintain its connectivity and functionality even after a large fraction of nodes were removed. However, they found that the network was vulnerable to targeted attacks, meaning that it could lose its connectivity and functionality after a small fraction of nodes were removed. They also found that the network had different levels of vulnerability depending on the centrality measure used to select the nodes for removal. For instance, the network was more vulnerable to attacks based on betweenness centrality than on degree centrality, because betweenness centrality captured the importance of nodes as bridges or bottlenecks in the network.

The evaluation of the network resilience to disruptions and failures can provide guidance for designing and implementing contingency plans and recovery strategies for the ATM system. For instance, random failures can be mitigated by increasing the redundancy and diversity of the network, while targeted attacks can be prevented by enhancing the security and protection of the network. Moreover, different types of disruptions and failures can require different types of responses depending on their impact on different parts of the network [4, 5].

Network optimization for performance improvement. The ATM system aims to achieve high levels of performance in terms of safety, capacity, efficiency, predictability, environment, and cost-efficiency. These performance areas are interrelated and often conflicting, meaning that improving one area can compromise another area. Therefore, there is a need to find optimal solutions that can balance and harmonize these performance areas according to the objectives and preferences of the stakeholders involved in the ATM system.

One example of applying CNT to optimize the network performance is the work by Zhang et al. (2019), who studied the US ATM network using data from FAA. They constructed a network where nodes were airports and links were flights between them. They proposed a multi-objective optimization model that considered three performance indicators: flight delay (the difference between actual and scheduled arrival times), flight distance (the length of flight routes), and flight fuel consumption (the amount of fuel consumed by flights). They used a genetic algorithm to find Pareto-optimal solutions that minimized these indicators simultaneously. They compared these solutions with the actual flight data and evaluated their potential benefits [5, 6].

They found that their optimization model could reduce flight delay by 19.8%, flight distance by 2.4%, and flight fuel consumption by 2.6%, compared with the actual flight data. They also found that their optimization model could generate different trade-offs among these indicators depending on the weights assigned to them. For instance, they found that reducing flight delay had a positive effect on reducing flight fuel consumption, but a negative effect on increasing flight distance.

Results

The optimization of the network performance can provide recommendations for planning and managing the ATM system according to different scenarios and criteria. For instance, flight delay can be reduced by adjusting flight schedules or rerouting flights, flight distance can be reduced by implementing direct or optimal routes, and flight fuel consumption can be reduced by applying speed or altitude control. Moreover, different performance indicators can reflect different interests or values of different stakeholders in the ATM system, such as passengers, airlines, ANSPs, or regulators [6].

Some of the main advantages and disadvantages of using complex network theory in air traffic control (ATC) are:

Advantages:

Complex network theory can provide a systematic and comprehensive way to model and analyze the air traffic system, by considering the aircraft as nodes, and the potential conflicts or interactions between them as links.

Complex network theory can measure and evaluate the complexity of air traffic from different perspectives, such as the conflict complexity, the situation complexity, and the intervention complexity, by using various network metrics and analysis methods.

Complex network theory can enhance the situation awareness and decision making of air traffic controllers, by providing them with objective and accurate indicators of air traffic complexity, such as the number and severity of conflicts, the diversity and uncertainty of aircraft states and behaviors, and the amount and intensity of ATC interventions.

Complex network theory can help design and implement intelligent support tools for air traffic controllers, such as conflict prediction, situation assessment, intervention recommendation, and complexity management, based on the complex network analysis methods and the machine learning techniques.

Complex network theory can optimize the design and operation of air traffic networks, such as the network topology, the network capacity, the network robustness, and the network efficiency, by using the complex network metrics and the network optimization methods.

Complex network theory can explore the co-evolution and interdependence of air traffic networks and other related networks, such as the urban network, the transportation network, and the communication network, by using the multilayer network theory and the network dynamics models.

Disadvantages:

Complex network theory requires collecting and processing large-scale and high-dimensional data of air traffic networks, such as the flight trajectories, the aircraft states, the ATC instructions, and the environmental factors, which can be difficult and costly.

Complex network theory involves modeling and simulating the air traffic system, which can be complex and uncertain, due to the nonlinear and stochastic dynamics, the human factors, the operational constraints, and the emergent phenomena.

Complex network theory faces the trade-off and coordination between the performance and safety objectives, such as the network capacity, the network efficiency, the network robustness, and the network resilience, which can be challenging and conflicting.

Complex network theory needs to integrate and validate the intelligent support tools for air traffic controllers, which can raise issues of compatibility, usability, reliability, and acceptability [7, 8].

Discussion

As mentioned above the complex network topology is a fascinating topic that explores the structure and function of various real-world systems, such as social networks, biological networks, technological networks, and more. Different scientists have conducted research on this topic and obtained various results, depending on their methods, models, and applications. For example, *Angélica Sousa da Mata* in her paper named *Complex Networks: a Mini-review* provides a brief overview of complex networks, including fundamental quantities, examples of network models, and the role of network topology in dynamical processes such as epidemics, rumor spreading, and synchronization. The paper also discusses some of the main contributions and challenges in this field, and provides references for further reading. *Coordination and Control of Complex Network Systems With Switching Topologies: A Survey* by *Zhiyong Sun*, *Xiangyu Meng*, and *Brian D.O.* surveys the coordination and control of complex network systems with switching network topologies, which means that the network structure can change over time. The paper focuses on the relationships between the switchings among different topology candidates and the network controllability, and between the switchings among different topology candidates and the emergence of coordination behaviors such as synchronization, consensus, and containment. The paper also reviews some of the analytical approaches and techniques for studying the stability and performance of such systems. In the *Topologies of Complex Networks: Functions and Structures* by *Lun Li* presented a novel approach to model and analyze the topologies of complex networks, especially the router-level topology of the Internet. The approach combines graph-theoretic properties, engineering intuition, and networking reality, and aims to capture the essential features and functions of the network structure. The thesis also proposes a new network generation algorithm that can produce realistic network models that match the measured data well. Moreover, despite numerous studies on CNT, the application of CNT in the field of ATC has not been sufficiently studied [9, 10, 11].

Conclusion

In this article, we have reviewed some of the applications of CNT to model the process of regulating air traffic with an increase in the intensity of flights. We have focused on three main aspects: the network topology of the ATM system, the network resilience to disruptions and failures, and the network optimization for performance improvement. We have shown that CNT can provide useful metrics and tools to measure and compare the properties of different networks, as well as to model and simulate their behavior and evolution under various conditions and scenarios. We have also shown that CNT can provide insights into the functionality and efficiency of the ATM system, as well as guidance for designing and implementing contingency plans and recovery strategies, and recommendations for planning and managing the ATM system according to different scenarios and criteria.

CNT is a powerful approach to study and improve complex systems such as ATM. However, it also has some limitations and challenges that need to be addressed in future research. For instance, CNT requires accurate and reliable data sources to construct realistic and representative networks; CNT needs to consider dynamic and stochastic aspects of networks such as temporal variations or uncertainties; CNT has to deal with multiple scales and levels of networks such as local or global perspectives; CNT has to cope with multiple objectives and constraints of networks such as conflicting or competing performance areas; CNT has to account for human factors and social aspects of networks such as behaviors or preferences [11, 12].

We hope that this article has provided an overview of some of the applications of CNT to model the process of regulating air traffic with an increase in the intensity of flights, as well as some of its benefits and challenges. We believe that CNT is a promising approach to enhance the performance and resilience of the ATM system in a complex and dynamic environment [13].

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