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Research on Optimization of Freight Loading for DF Airlines with Centre of Gravity Constraints

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Abstract

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The research object of this thesis is DF Airlines, which owns 15 full cargo aircraft, including 2 B747-8Fs. The purpose of this study is to improve the loading method of DF Airlines' cargo planes. Improve the loading efficiency of cargo planes while ensuring their smooth flight.

Simply put, optimizing the loading method of air cargo can improve the utilization of cargo aircraft space, in order to use more space to load more cargo. But when loading the goods onto the cargo plane, it is also necessary to consider the placement position of the goods to ensure that the final cargo plane's centre of gravity is within a reasonable range.

This thesis analyses the constraints that need to be followed during the loading process and uses case analysis methods to optimize the utilization of cargo aircraft loading space. Part of the data was obtained through calculations, while some data was provided by DF Airlines. Analyse the data using Power BI and Excel Pivot tools.

This case study was conducted on a batch of cargo to be loaded by DF Airlines. This thesis obtains the relationship between loadable weight and the ratio of gross weight to volume weight of goods, as well as the relationship between the average density of loaded goods and revenue. By comparing with the previous loading methods of DF Airlines, it was found that cargo loading under the constraints of overall cargo density and light to heavy cargo ratio can indeed improve the space utilization of cargo planes, allowing them to load more cargo and increase revenue.

Key words
Loading method, Quantitative analysis, Centre of gravity constraints, Pallets, Air cargo aircraft

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1 Introduction

This chapter mainly introduces the background, research significance, and basic thesis framework of this thesis. The purpose is to provide readers with a certain understanding of the current freight business loading methods and the loading issues that need to be addressed in this thesis.

1.1 Research background

At present, with the rapid development of various aspects such as society, economy, and technological progress, it has promoted the rapid development of the air transportation industry, which has led to a continuous increase in the number of cargo planes of various airlines. In air freight, in order to reduce aviation logistics costs, minimize loading and unloading time, and improve logistics efficiency, various airlines use packaging containers with certain specifications and strength, such as containers and pallets, to meet the needs of suppliers or demanders. Due to the use of larger cargo containers such as containers and pallets, airlines not only shorten the loading and unloading time of goods but also reduce labour costs by centralizing the loading and unloading of goods during the transportation process.

When loading regular containers on cargo planes, it is not only necessary to consider loading efficiency but also whether the aircraft's centre of gravity is within the range of deviation from the actual centre of gravity. Unscientific cargo loading schemes not only reduce the utilization rate of cargo compartments but also affect the operational safety of aircraft. According to data on aircraft accidents related to cargo aircraft load worldwide, the proportion of accidents caused by incorrect loading and centre of gravity not within the safe range exceeds 50%.

This thesis analyses the constraints that need to be followed during the loading process, and uses case analysis methods to optimize the utilization of cargo aircraft loading space, in order to improve the loading method of DF Airlines' cargo aircraft. Improve the loading efficiency of cargo planes while ensuring their smooth flight. Provide new ideas and methods for air freight companies to load. Quantitative and qualitative analysis methods were used for data collection. Quantitative analysis is the main analysis method of this thesis, which mainly analyses a batch of cargo to be loaded by DF Airlines, providing the optimal loading plan for maintaining the total cargo density on the loaded aircraft at a certain density and maintaining a certain proportion of light and heavy cargo. Qualitative analysis mainly includes analysing the process of changes in loading methods and understanding their loading methods from DF Airlines staff.

1.2 Research Significance

So far, for air cargo aircraft, the most important thing is to ensure the flight safety of the aircraft, that is, to ensure that the centre of gravity of the aircraft does not exceed the allowable range of the actual centre of gravity after efficient cargo loading, and to approach its minimum error value as much as possible.

DF Airlines is committed to building China's first and world-class air cargo carrier. Due to the numerous regions involved in DF Airlines' cargo business, it is also one of the top 5 airlines in China with a large number of cargo planes. DF Airlines has more than one type of cargo aircraft, so the internal size of the cargo aircraft is relatively different. The cargo loading method is mainly based on the experience of the loader or the use of software such as Load Master to determine the loading method of the cargo plane. Empirical loading can lead to low efficiency in cargo loading, and experience needs to be constantly tried to obtain a rough estimate, but its time cost will also greatly increase. Software based loading can improve loading efficiency to a certain extent, but the efficiency is not too high, and software operation also has certain difficulties, resulting in low loading efficiency. Therefore, the main problem currently faced by cargo aircraft loading is to handle the diversity and particularity of air freight materials, (such as size, centre of gravity, etc.) design the loading method reasonably, and maximize the cargo loading while keeping the centre of gravity within the allowable range after cargo aircraft loading.

As an indispensable transportation method in logistics activities, the loading efficiency of cargo planes is related to the economic development of enterprises. Therefore, the optimization design of cargo loading methods based on centre of gravity constraints has the following two meanings: firstly, it helps DF Airlines improve the space utilization rate of cargo loading. Secondly, it helps DF Airlines' cargo planes improve their stability and reduce fuel consumption during flight.

1.3 Introduction to Thesis Structure

The theoretical framework of this thesis describes the business model of air cargo, the profitability of air cargo, and the development process of cargo loading methods. This enables readers to understand the aviation cargo business, understand the diversity of cargo loading methods, the importance of efficient loading for aviation cargo business, and the impact of aircraft centre of gravity on cargo loading. In addition, the main purpose of this thesis is to study the optimization of cargo loading in order to improve the utilization of cargo aircraft space, so that it can load more cargo and increase the revenue of airlines. Due to the complexity of this topic analysis, the thesis will make assumptions in certain aspects, such as treating the cargo plane as a regular rectangular container with a cargo hold loading space and a cargo centre of gravity at its centre. These assumptions are for the convenience of subsequent calculations.

This thesis is divided into six chapters, with references and appendices at the end. The first chapter introduces the research background, purpose, and significance of this thesis. Then the general framework of this thesis was introduced. The second chapter introduces the air cargo model, the profitability of the air cargo business, and the outlook for the air cargo transportation industry.

The third chapter mainly focuses on the research of air cargo loading, providing optimization solutions for loading goods into pallets or containers from the perspective of loading optimization. In addition, different methods of loading cargo from pallets or containers into the interior of the aircraft were explored based on the constraints of the aircraft's centre of gravity.

Chapter 4 mainly discusses the research process, namely the loading problem and constraint conditions of cargo planes. Chapter 5 is the empirical part, which discovered the optimal density for cargo loading on cargo planes. At the same time, it was also found that the ratio of light to heavy goods has an impact on the charging of goods. Chapter 6 presents the specific optimization results of this loading method in the form of examples, as well as how to load it onto the cargo plane. Chapter 7 introduces the conclusion of this thesis. The following are the references and appendices of this thesis.

2 Air freight business framework

This chapter mainly outlines the framework of freight business. In airport business, freight business is one of the main sources of revenue in airport business. A brief analysis was conducted on the operational model, profitability, and future development of the freight business.

2.1 Air freight business model

With the widespread development of international air cargo business, the air cargo model has also received attention from the global academic community. The domestic academic community focuses on studying the current development status and existing problems of domestic air freight, in order to analyse the business model of air freight and propose corresponding suggestions.

For example, Xiaokang Liang focuses on analysing the main problems that arise in the current business model of air freight logistics, taking into account the current business model. Based on the background of the times and social needs, propose effective strategies for the development of the business model of air cargo logistics, thereby effectively promoting the sustainable and stable development of air cargo logistics. (Xiaokang Liang 2021, 9-10.) Hang Sun, based on the current development status of air freight, proposed the opportunities faced by the development of air logistics multimodal transport and the feasibility of its implementation, analysed the prospects of air multimodal transport, and provided solutions to potential problems in development. Research has found that in the context of multimodal transportation, air containerization is the future development direction, and airports should respond to multimodal transportation strategies, improve overall transportation efficiency, and promote the development of air freight. (Hang Sun 2020,196-197.)

The research in this field in foreign academic circles is more comprehensive and systematic, not limited to macro political and economic conditions, but focuses on the detailed factors of actual business operations. Ayasanond conducted literature analysis and in-depth interviews with over 20 management personnel in Thai Airways' human resources, air cargo operations, training departments, ground services, corporate communication, public relations, and customer service departments. Based on PEST analysis, Porter's Five Forces model, and SWOT analysis, it was found that the main factors affecting Thai Airways' supply chain management are global commercial competition, security, and one-stop services, the open sky policy of commercial airlines, the growth of online technology, and changes in consumer behaviour. (Ayasanond 2019, 365-373.) Rabten et al. used the fuzzy analytic hierarchy process to conduct in-depth analysis of survey data from Bhutanese air cargo management experts, and determined that the cargo handling infrastructure is the most in need of improvement, followed by airport fees and cargo security services, in order to determine an effective cargo business model for the airport. (Rabten 2018, 40-45).

2.2 Profitability of Air Cargo Business

Profitability analysis indicators are the core of financial analysis. Therefore, the profitability of the aviation industry is not only of practical significance but also of indispensable social significance for its development.

Wang Wang pointed out that in recent years, China's air transportation industry has continued to grow rapidly, and it is expected that 258 new airports will be built in China by 2023. China has formed three major regional airport groups: the northern airport group dominated by Beijing, the eastern airport group dominated by Shanghai, and the central southern airport group dominated by Guangzhou. The southwestern airport group dominated by Chengdu, Chongqing, and Kunming, and the northwest airport group dominated by Xi'an and Urumqi are forming their embryonic forms. The formation of these five major airport clusters has laid the foundation for a comprehensive airline network. (Wang Wang, 2017.)

A report released by the Civil Aviation Administration in 2022 shows that in recent years, the overall profit level of China's aviation logistics enterprises has shown a high-speed growth trend. Mainly because, on the one hand, with the continuous improvement of China's socio-economic development level and active participation in international trade activities, it has brought about an increasing demand for aviation logistics. On the other hand, under the influence of the COVID-19, international air transport capacity is in short supply, which has led to the rise of air logistics prices. At the same time, the main procurement costs of aviation fuel, aircraft, and aviation materials have not significantly increased to the same extent.

In the future, with the gradual weakening of the impact of the COVID-19, the global supply chain will return to normal, the market supply and demand relationship is expected to rebalance, and the aviation logistics industry will return to normal development. As shown in Figure 1. (CAAC 2022.)

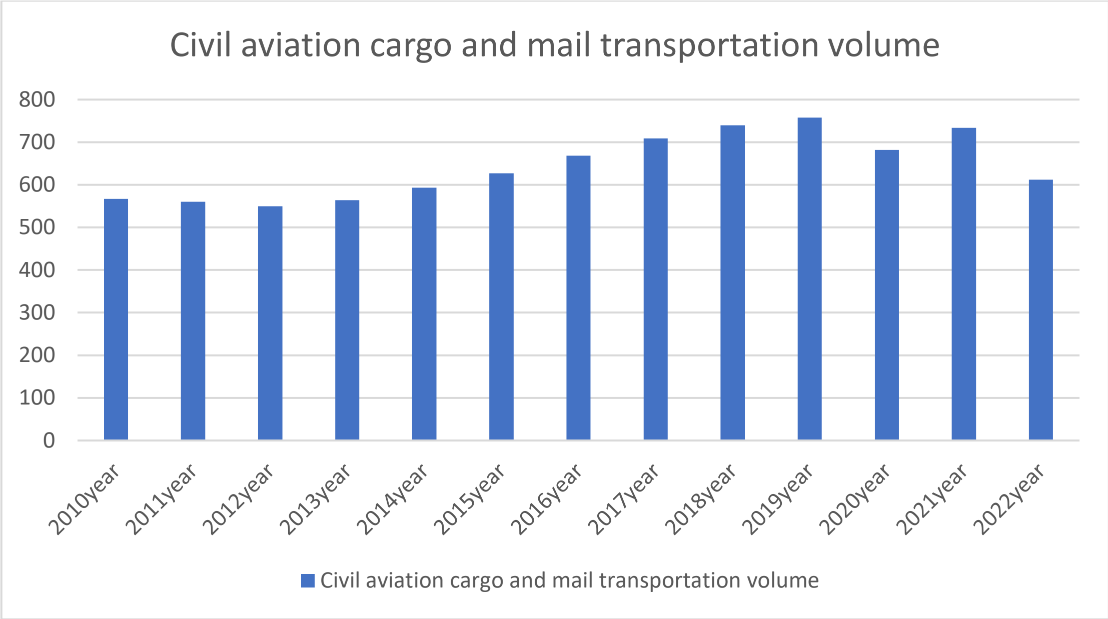

Figure 1 Civil aviation cargo and mail transportation volume (unit: 10000 tons)

According to the International Air Transport Association (IATA), the net profit of the global air transport industry in 2018 was 30 billion US dollars. In 2019, the net profit of the global air transportation industry reached $25.9 billion. This is the tenth consecutive year of profitability in the global air transportation industry. In 2020, due to the impact of the epidemic, global air passenger transportation basically stagnated, and the global air transportation industry suffered a net loss of 126.4 billion US dollars. With the gradual improvement of the epidemic, IATA predicts that the global air transportation industry will lose $47.7 billion in 2021. Although the loss margin has narrowed, it is still difficult to recover profits. As shown in Figure 2.

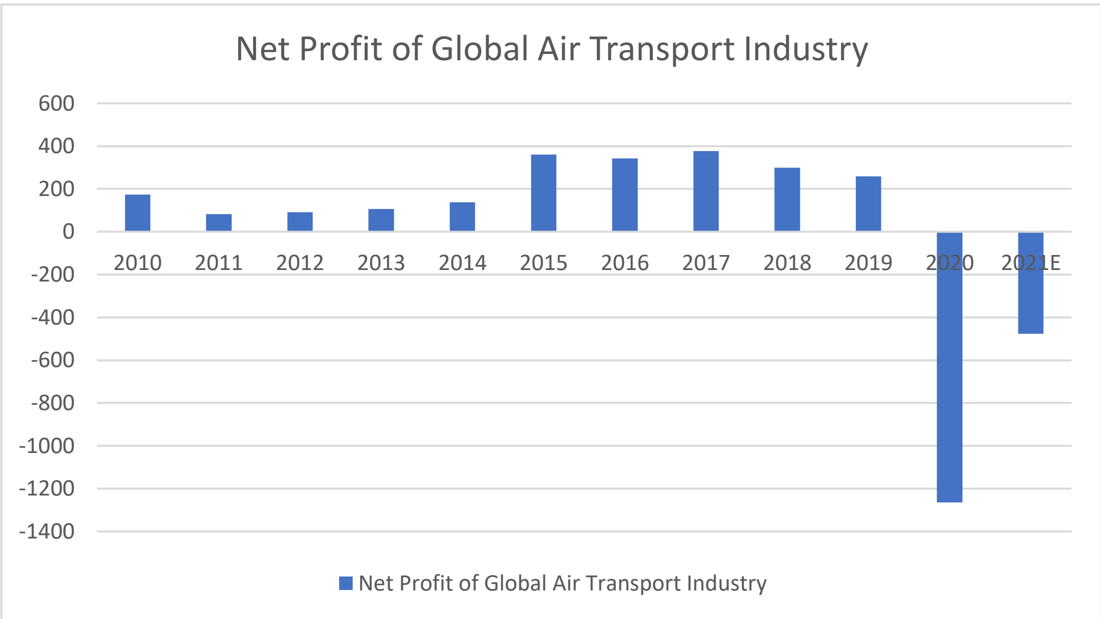

Figure 2 Net Profit of Global Air Transport Industry (Unit: 100 million US dollars)

Air freight benefits from the global demand for transportation of vaccines and other anti-epidemic materials, and is relatively less affected by the epidemic. From 2010 to 2018, the overall global air cargo volume maintained an upward trend, with a slight decline in 2019 and a significant decline of 9.1% in 2020 due to the impact of the epidemic. It is expected that the global air cargo transportation volume will quickly recover to 63.1 million tons in 2021. As shown in Figure 3. （IATA 2021.）

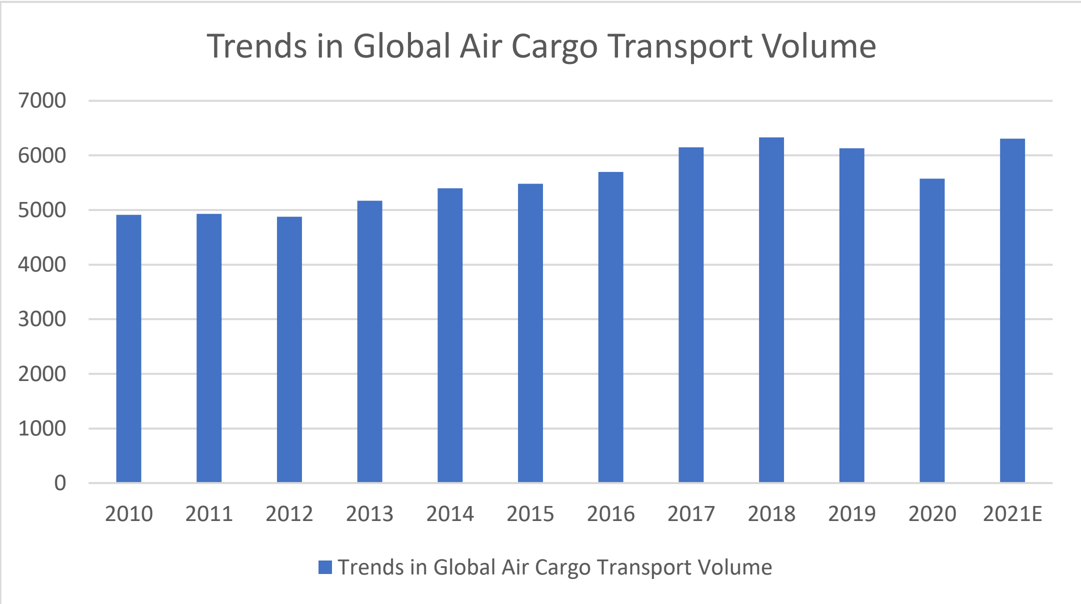

Figure 3 Trends in Global Air Cargo Transport Volume (Unit: 10000 tons)

2.3 Outlook for the Air Cargo Industry

Currently, China has entered a critical period of transformation and development from traditional aviation logistics to modern aviation logistics. On the one hand, with the increasing trend of economic globalization and integration, the demand for China's air cargo market is growing day by day. On the other hand, with the continuous transformation and upgrading of the manufacturing and retail industries in recent years, the rapid development of modern logistics formats such as e-commerce, express delivery, and cold chain has led to structural changes in the air cargo market. Attract domestic and foreign logistics integrators and freight airlines to gradually open freight routes between key cities. (CIRN 2023.)

The International Air Transport Association forecasts China's international air cargo market according to three scenarios: benchmark, optimistic and pessimistic. Under the benchmark scenario, overseas demand is expected to contract as scheduled, and it is expected that China's international air cargo transportation volume will reach approximately 2.45 million tons, a year-on-year decrease of about 7%. In an optimistic scenario, the decline in overseas demand is relatively slow, and it is expected that China's international air cargo will decrease by about 1% year-on-year, completing a transportation volume of about 2.6 million tons. Under a pessimistic scenario, external demand is severely weak, and it is expected that China's international air cargo transportation volume will reach approximately 2.35 million tons, a year-on-year decrease of about 11%. As shown in Table 1. (IATA 2023.)

Table 1 The completed cargo and mail transportation volume of China's international routes (unit: 10000 tons)

Scenario	2019	2020	2021	2022	2023(E)		
	the volume of freight transport	the volume of freight transport	the volume of freight transport	the volume of freight transport	the volume of freight transport	Year-on-year change	Change compared to 2019
Benchmark	241.9	223.1	266.7	263.8	245	-7%	1%
Optimistic					260	-1%	7%
Pessimistic					235	-11%	-3%

According to the above data, China's freight business has decreased in the past 23 years. But in the long run, with the development of aviation logistics, aviation logistics enterprises are no longer simply providing logistics and transportation services. The entire industry has formed a chain of air freight services, which is conducive to the development of China's freight business.

3 Development of Research on Optimization of Air Cargo Loading

Pallets and containers are the two most important inventions in the history of logistics in the 20th century. The value of pallets runs through the entire logistics process, regardless of loading, unloading, handling, storage, sorting, and transportation. Its most significant value lies in the significant systematic improvement of logistics operational efficiency through consistent intermodal transportation. Due to the increasing use of pallets, the production types and sales quantities of pallets have also increased sharply. The production materials of pallets are gradually diversified based on usage scenarios. The types of pallets vary depending on the application scenario. Due to the differences and complexity in economic systems, development levels, and pallet pooling practices in various countries, the organizational models of pallet operations have also shown diversification, and various innovative models have emerged endlessly. As of 2019, the global pallet stock is estimated to reach 6 billion pieces.

In recent years, the development of China's pallet industry has laid a good foundation, with continuous expansion of pallet production capacity, continuous promotion of standardization work, and an increasing number of application scenarios. With the transformation, upgrading, and continuous development of China's industry, the current Chinese pallet industry has entered a period of transformation and upgrading, which is also a new window period for foreign cooperation. (Jin Cai 2021, 11-22.)

Hong Zhao and Lihong Liu investigated and studied the current situation of pallet use in China. In response to the problems existing in the actual use of the current standard "Sichuan style" tray in China, the tray structure has been optimized and improved based on international advanced experience, and local standards have been formed. It is of great significance for improving the pallet standard system, promoting the circulation and sharing of standard pallets, and regulating the development of regional logistics. (Hong Zhao & Lihong Liu 2019, 210-211.)

3.1 Factors affecting the development of air cargo loading

Due to the fact that in actual loading operations, many special constraints may be encountered, such as the special nature of the goods requiring special loading methods, different pallet structure materials, and the special requirements of the cargo owner, which are all constraints for loading problems. A more practical and effective solution to the set loading problem requires more in-depth and detailed research on current loading methods and optimization theories.

Dehao Lin believes that there are still many shortcomings in his research when considering operation friendly loading optimization. Due to the complexity of loading issues and actual constraints, as well as the inherent flaws of heuristic algorithms, such as the fact that heuristic algorithms require a considerable amount of runtime for larger instances, there is still much room for improvement. (Dehao Lin 2020.)

Haiqiang Xie, through the development of virtual simulation systems and in-depth research on related issues, also recognizes that there are still many issues that need to be further studied regarding loading issues. For example, if it uses constructive heuristic algorithms to plan the cargo loading process, involving more realistic and complex problem models, both the algorithm model and system implementation will face more complex problems. The problem it studies focuses on the packing of weakly heterogeneous goods, and more factors need to be considered when packing heterogeneous goods. (Haiqiang Xie 2019.)

When He Zhu studied the optimization of cargo loading, he assumed the type of cargo to be regular rectangular cargo, without considering irregular cargo and irregular pallet types, with limited constraints. The purpose of doing so is to make modeling and designing solving algorithms more convenient. In the future, further research is needed on the loading of irregular cargo and irregular containers in air cargo. Make the research questions more in line with practical aircraft loading problems. (He Zhu 2018.)

3.2 Airlines' Views on Optimizing Air Cargo Loading

Air freight has become an important component of modern logistics due to its large loading capacity and fast delivery, and aircraft loading optimization is an important link related to air transportation efficiency. The shipping cost of air freight companies is based on the larger weight of gross or volumetric weight, so airlines are very concerned about how to optimize the loading of goods and improve the utilization of cargo cabin space.

Lv Mingli mentioned in her research on optimization strategies for cargo loading management in airlines. With the accelerated development of globalization and e-commerce, as well as the gradual improvement and maturity of domestic air freight policy system. The development momentum of the air cargo industry is rapid, with huge potential, and the market demand for air cargo products is also increasing day by day. The high operating costs and increasingly fierce market competition are closely related to the advantages of high safety and fast timeliness of air freight. Airlines are gradually realizing that optimizing cargo loading management and increasing loading rates are important aspects that freight airlines must consider to reduce operating costs per unit of cargo, enhance their competitiveness, and maintain sustainable development. (Lv Mingli 2020.)

Lixia Zhang mentioned that with the stable development of international trade and the world economy, global interactivity will continue to strengthen, and the air transportation industry will grow at a relatively fast pace. The competition in the air transportation market is also becoming increasingly fierce. In the past, airlines have always placed air cargo in a secondary position, and with the changing situation, air cargo has gradually gained attention. More and more airlines are investing more energy in the cargo market, and air cargo has become a new economic growth point for China's civil aviation industry. The study of air cargo loading issues plays a positive role in promoting the development of air cargo, and has certain theoretical and practical value. (Lixia Zhang 2012.)

3.3 The driving factors for optimizing cargo aircraft loading

Air transportation is currently the most modern mode of transportation. A reasonable loading plan can maximize flight safety and cargo transportation safety, reduce fuel consumption during flight, and optimize the cost structure of airlines.

Peng Li, Fei Wang and Guiyuan Li believe that cargo loading always occupies an important position in the air cargo transportation process. Whether the loading of air cargo meets the requirements is directly related to flight safety and the profitability of the airline. How to maximize the utilization of cargo loading space and load capacity, and achieve the best safety, is the unremitting goal of air cargo loading and transportation. (Peng Li, Fei Wang & Guiyuan Li. 2022b, 67-69.)

In her research, Jing Lu mentioned that the booming development of air freight has also led to increasingly prominent problems. The main concentrated performance is low service quality, increasingly fierce competition, and a decrease in profit margins. In order for airlines to take the lead in fierce market competition, in addition to establishing a strong air transportation network, it is more important to improve service quality, reduce operating costs, and thereby improve the company's operational efficiency. Therefore, the issue of aircraft cabin loading also determines a series of core competitiveness levels of airlines, such as operating costs, efficiency, service speed, and service scope, and has important strategic significance. (Jing Lu 2017.)

3.4 The process of changing the loading method

With the continuous development of international trade, traditional bulk transportation methods can no longer meet more and more trade needs. Pallets, as an effective way to improve the storage and transportation efficiency of goods, have been developed as a container in the logistics field to adapt to the mechanization of loading and unloading. With the continuous development of transportation technology, the transportation cost of pallets continues to decrease. Pallet transportation has advantages such as standardization and modularization, which can achieve standardized management and centralized transportation of goods, improving transportation efficiency and management level. However, how to achieve the combination of various goods to maximize space utilization is the most common and complex problem in cargo loading.

Li Peng ,Wang Fei and Guiyuan Li started with the concept and classification of air transportation loading optimization problems. Analyzed the commonly used heuristic algorithms for optimizing the loading of air cargo transportation, and proposed several issues that need to be noted in air cargo transportation loading. On the premise of ensuring the safety and rationality of cargo loading, it provides reference for achieving more efficient air cargo transportation. (Li Peng ,Wang Fei & Guiyuan Li 2022, 67-69.)

Chenyu Jin, Youtian Zahng, Hanwei Liu and Shan Wu established a multi-objective constraint model for air freight assembly of goods by considering various influencing factors such as different placement methods of goods, weight and size limitations of pallets. Using a hybrid heuristic algorithm mainly based on genetic algorithm and simulated annealing algorithm to run the solution, quickly formulate the loading layout plan for goods. It was found that this method can effectively solve the problem of air freight assembly strategy under multiple constraints. (Chenyu Jin, Youtian Zahng, Hanwei Liu & Shan Wu 2021, 70-77.)

Starting from the air cargo loading problem with loading sequence constraints, Changyong Zhang, Yiming Zhai, Qianqian Zhang and Yanfang Wang used anthropomorphic heuristic algorithms to construct cargo loading strategies. Optimize the solution through crossover and mutation operations in genetic algorithm, combined with various constraints of the tray. Select the cargo integration plan with the highest space utilization rate among feasible solutions and fix it on the pallet. Finally, an experiment was conducted using actual cargo data from a certain airport logistics company, and the operability of the loading plan was achieved. (Changyong Zhang, Yiming Zhai, Qianqian Zhang & Yanfang Wang 2021, 150-156.)

Haiqiang Xie is based on virtual reality technology to study the optimization problem of cargo loading. Simulate cargo loading operations and optimize the loading process. Create a virtual reality simulation platform for pallet loading. This provides a basic display platform for further in-depth research on loading optimization problems. And it can provide beneficial assistance for improving the speed of modular goods circulation. (Haiqiang Xie 2019.)

Yunfei Fan conducted research on the pallet loading problem from two aspects: heuristic algorithm and genetic algorithm. Construct a corresponding mathematical model that considers constraints such as space, placement direction, support area, and stability. A heuristic algorithm based on spatial triple segmentation and merging was designed. On the basis of meeting various constraints, maximize the merging and reuse of small spaces. (Yunfei Fan 2018.)

Antonio G. Ramos， Elsa Silva， Jose F further investigated the issue of placing the center of gravity of the pallet based on the vehicle used. They proposed a genetic algorithm based on fitness function, which considered static stability and load balance. They also provide an instance generator that includes not only project dimensions but also project weights. (Antonio G. Ramos， Elsa Silva， Jose F 2018, 1140-1152.)

Baoping Li aims to reduce accidents caused by unreasonable loading and fixation of goods on pallets, in order to avoid unnecessary losses for both the shipper and the carrier. Therefore, a force analysis was conducted on the pallet in the air transportation environment. Analyze the weight distribution of goods horizontally and vertically on the pallet based on the structural characteristics of the pallet bottom. Design a fixing scheme that meets the requirements of external forces and tray strength, and visually demonstrate the fixing method through Visio drawing. It has significant theoretical and practical significance. (Baoping Li 2017.)

Shih, Shiao Y L, Fei-Yen established a nonlinear mixed Integer programming model with the objective function of minimizing the total operating cost. The model was transformed into a linear model through linearization technology, and solved using a solver. It was found that the loading scheme generated by the model has certain reference value for airlines (Shih, Shiao Y L & Fei-Yen 2015, 555-575.)

Chien, Lee, Huang, and Wu have developed an effective computational program. This program involves three-dimensional space segmentation to determine the most ideal loading method. To minimize space waste and embed this program into the cargo loading support system. (Chien, Lee, Huang, and Wu 2008, 965-978.)

3.5 The Development of Loading Methods with Center of Gravity Constraints

The problem of cargo loading only considers the optimization of cargo loading, which is not comprehensive. It is also necessary to consider the center of gravity problem after the cargo is loaded onto the cargo plane. This is an important factor in whether an aircraft can take off and fly stably. For flight safety, the loading of cargo in the cabin, namely the optimization of aircraft weight and balance, has long been a concern of the academic community. The imbalance in pitch during aircraft loading may cause the aircraft's nose to become too heavy and difficult to take off. If the tail is too heavy, it will cause an excessive takeoff elevation and poor aerodynamic performance on the vertical and horizontal wing surface. Both of these situations can endanger flight safety.

Yongsheng Shi and Ce Wang established a loading model based on the constraints in the actual loading process, and discussed the zoning of the main cargo hold. Using genetic algorithm to obtain the loading plan for the main cargo hold with the goal of minimizing the center of gravity offset. It was found that this loading method has important theoretical value and practical significance for the study of air cargo loading problems. (Yongsheng Shi & Ce Wang 2020, 10517-10522.)

Huizhi Yang starts from the loading problem with center of gravity balance constraints. Although the hybrid Tabu search algorithm in the set loading problem meets the gravity balance constraint of the cargo collector, it has the disadvantage of low loading rate. Improvements are made to the G2LA algorithm in terms of selecting the loading order of goods based on the coding order of the taboo search algorithm and the evaluation function of the new complete loading scheme. Finally, the experimental results demonstrate the effectiveness of this algorithm. (Huizhi Yang 2015, 220-222.)

Vancroonenburg et al. proposed a multi-objective mixed Integer programming model. The first goal is to maximize the loading quantity of goods, and the second goal is to minimize the deviation of the aircraft center of gravity. This model involves a large number of constraints to ensure the integrity and stability of the aircraft, as well as safe and efficient unloading. The effectiveness of this model was verified through numerical examples, and it is applicable to most aircraft loading optimization problems. (Vancroonenburg et al. 2014, 70-83.)

Limbourg S，Schyns M，Laporte G considered the impact of cargo placement on the center of gravity of the aircraft, and assumed that the most suitable container had been selected. Its main purpose is to minimize the moment of inertia of the cargo to improve overall stability, reduce structural pressure on the aircraft, and reduce fuel consumption (Limbourg S，Schyns M，Laporte G 2012,1271-1283.)

Vertichel and Vancroonenburg attempted to determine how to select the cargo to be loaded on the aircraft. Pursue the maximization of air cargo profits and strive to minimize the deviation of the center of gravity. A mixed Integer programming model is established, and the effectiveness and efficiency of the model are verified. (Verstichel et al. 2011, 1051-1059.)

3.6 Method selection

After reading the literature on loading optimization mentioned above, it was found that there are mainly genetic algorithms, heuristic algorithms, search algorithms, simulated annealing algorithms, etc. for the air cargo loading method. The research on air cargo loading methods in China is still in an immature stage. Although there has been some research on the loading methods of air cargo, it is rare to apply them to practical problems. It is still necessary to conduct practical analysis based on actual problems and find better solutions for them.

Compared to the research situation of domestic scholars, foreign scholars tend to consider establishing models through a series of constraints when studying the air cargo loading methods. However, due to the wide variety and different forms of goods loaded by air, a series of complex considerations need to be taken into account during loading. Existing research generally only considers some of the constraints, and if one considers the research one by one, its complexity will also increase accordingly, thus affecting its practical value to a certain extent.

When solving the cargo aircraft stowage problem, most scholars use mixed integer linear programming model to express the problem they want to solve. However, the problems solved are different, and the objective functions in the model are also different. Therefore, when establishing the model, it is necessary to establish it based on the problems solved. This thesis will optimize and improve the cargo loading method of DF Airlines, study the loading problem through a series of constraints, improve the loading rate of DF Airlines, and save cargo aircraft space. This thesis first analyzes the constraints that need to be followed during the loading process, and uses case analysis methods to optimize the utilization of cargo loading space. Based on the mixing and matching of light and heavy goods, find the most suitable matching ratio, improve the loading efficiency of each pallet, and save more space for the cargo plane to load other goods. Part of the data was obtained through calculations, while some of the data was provided by DF Airlines. Then, under the constraint of the center of gravity and ensuring that the cargo plane can fly smoothly, the cargo is loaded into the cargo plane according to a certain loading method.

3.7 Reliability and Validity

Reliability refers to the consistency of measurement results. If a certain instrument is used for testing and the results of the subjects being tested in the first and second attempts are the same, then it is considered reliable. And validity depends more on the strength of the assumed results.

Firstly, the data source of this thesis is. In order to better understand the situation and ensure the reliability and validity of the research, a series of data in the freight business of this thesis were searched from official websites such as IATA and CAAC. The data was analyzed using Excel Pivot, with some being analyzed by Power BI. Some constraint data related to B747-8F is also sourced from Boeing's official website. At the same time, the structural restriction manual of the cargo plane was also checked on the official website of DF Airlines to ensure the reliability of the constraint conditions. In the literature review, trustworthy resources were used to search for academic thesiss, research processes, and achievements from others on CNKI. It is also searched from professional textbooks, International Air Transport Association, CAAC and other international regulatory and professional websites.

4 Research process

This chapter mainly introduces the main issues to be discussed in this thesis and how to improve the utilization of cargo aircraft space under the constraint of center of gravity. And analyze the constraints that will be faced when discussing and solving this problem, and ultimately obtain the objective function required for this thesis.

4.1 Problem Description

Air cargo planes are generally composed of one or more cargo compartments, where standard containers can be loaded into each cargo compartment. Unreasonable aircraft loading can cause the actual center of gravity to deviate from the limit range of the target center of gravity. During flight, if the center of gravity deviates too much, it can cause control difficulties and even flight accidents. When a cargo plane flies, its stability is largely determined by the position of its center of gravity. To ensure flight safety, the center of gravity of the cargo plane must be within the specified allowable range and must not exceed this range, otherwise its safety will not be guaranteed. If the center of gravity of the cargo plane is relatively forward, it will cause the nose to be overweight, and if the center of gravity is relatively backward, it will cause the tail to be overweight. Only when the center of gravity is within the given target range can the wing achieve the optimal balance of lift and drag caused by air, thus achieving a level and stable flight of the cargo plane.

When a cargo plane flies, its stability is largely determined by the position of the cargo plane's center of gravity. In order to ensure flight safety, the center of gravity of a cargo plane during flight must be within the specified allowable range and must not exceed this range, otherwise its safety will not be guaranteed. The longitudinal coordinates of the center of gravity, also known as the reference reference plane, are extremely important, and the center of gravity at different positions will affect the pilot's control of the entire cargo plane's pitch angle. If the center of gravity of the cargo plane is relatively forward, it will cause the nose to be overweight, and if the center of gravity is relatively backward, it will cause the tail to be overweight. Only when the center of gravity is within the given target range and this deviation is minimized as much as possible, can the lift and drag generated by the air on the wing achieve optimal balance, thereby achieving horizontal and stable flight of the cargo plane.

4.2 Constraints

The purpose of the optimization problem of air cargo aircraft loading studied in this thesis is to improve the loading efficiency of cargo aircraft and load as much cargo as possible. When placing goods on pallets, pay attention to the combination of light and heavy goods. When placing containers on the arrival cabin, it can ensure the safe flight of the aircraft. This thesis has the following assumptions: 1. The goods to be loaded can be packaged into regular rectangles. 2. The starting and ending points for the transportation of this batch of goods are the same, and there is no situation of unloading midway. 3. Use standardized containers. 4. The loading space of the cargo hold is a regular rectangular container, and the cargo hold size is L × W × H。 5. There must be the same gap d between adjacent goods to facilitate lateral fixation of goods and personnel inspection during air transportation. 6. Establish a Cartesian coordinate system system, take the longitudinal central axis of the aircraft as the x axis, and set the lift point O of the aircraft as the origin (generally in the center of the fuselage). The constraints established in this thesis include the different attributes of cargo, pallet (PLT), cargo holds, and the actual situation during operation. Table 2 represents the decision variables and related parameters.

Table 2 the decision variables and related parameters

symbol	illustrate
x_{ij}	（i=1，2，3,…,N）0-1 as variables，Cargo i loaded into pallet j，then x_{ij}=1,otherwisex_{ij}=0
w_i	Weight of cargo i（i=1，2，3,…,N_{PLT}）
V_i	Volume of cargo i（i=1，2，3,…,N_{PLT}）
a_i、b_i、c_i	The length, width, and height of cargo i（i=1，2，3,…,N_{PLT}）

The basic constraints of goods and pallets are shown in equations (1) to (4). Equations (1) to (2) indicate that both goods x_{ij} and y_{jk} are 0-1 variables; Equation (3) indicates that each PLT can only be placed in one compartment. Equation (4) indicates that at most one pallet can be placed on each cabin. Among them, POS represents cabin space.

$$x_{ij}\begin{cases}1, If\ cargo\ i\ is\ placed\ in\ PLT_j\\ 0,\ other\end{cases}$$

i=1, 2, 3,…,N, j=1, 2, 3,…,N_{PLT} (1)

$$y_{jk}\begin{cases}1,\ PLT_j\ placed\ on\ cargo\ hold\ k\\ 0,\ other\end{cases}$$

j=1, 2, 3,…,N_{PLT}, k=1, 2, 3,…,N_{pos} (2)

$$\sum_{k=1}^{N_{Pos}} y_{jk} \leq 1, \quad j = 1,2,\ldots,N_{PLT} \tag{3}$$

$$\sum_{k=1}^{N_{PLT}} y_{jk} \leq 1, \quad k = 1,2,\ldots,N_{POS} \tag{4}$$

4.3 Goods specific attributes

During the process of aircraft loading, if the cargo density is high and the cargo plane has not yet reached its maximum load before it is fully loaded, the cargo plane has more space but cannot exceed the specified weight, which can lead to waste of space. On the other hand, if the cargo plane is loaded with mostly light foam cargo, there may be a situation where the cargo plane space is already filled, but it has not reached or even far less than the load value.

Air freight companies charge fees based on the weight of heavy cargo and the volume of light cargo. When the actual weight is less than the volume weight, this type of goods is considered as light foam goods, and the larger weight of the two is taken as the billing weight, which is generally the volume weight of the goods. For inherently heavy goods, the chargeable weight is equal to the gross weight of the goods. So, only by balancing the quantity relationship between heavy and light goods can we ensure the maximization of profits from this loading. In air freight, 6000 cubic centimeters is 1 kilogram, which means that when the volume unit is cubic centimeters, the constant is 6000, and when the volume unit is cubic feet, the constant is 0.21191.

The ratio of the heavy cargo density to the light cargo density of a batch of goods on the same cargo plane is called DRHLG, and the higher this value, the greater the density difference of this batch of goods. On the contrary, the lower this value, the closer the density of the transported goods is. In equation (5), the density is less than 4 72 (i.e. 1/0 2119) is defined as light cargo (I=0), otherwise it is heavy cargo (I=1).

$$\mathrm{I} = \begin{cases} 1, & \text{if } \frac{\mathrm{w}}{\mathrm{v}} \geq 4.72 \\ 0, & \text{if } \frac{\mathrm{w}}{\mathrm{v}} < 4.72 \end{cases} \tag{5}$$

Because the space and weight that each aircraft can carry are limited and fixed. So the larger DRHLG, the more obvious the polarization between light and heavy cargo, indicating a low utilization rate for cargo aircraft. Either the weight has reached its maximum and there is still a lot of space left, or there is very little space left, but it is far from reaching the load weight that the cargo plane can withstand. Therefore, in order to fully utilize the space and load weight of the cargo plane, it is necessary to reasonably combine and optimize the waiting goods before loading them into the cargo plane. As shown in equation (6). D is the optimal load density of the cargo plane. It is the ratio of the effective weight that a cargo plane can load to the effective volume that it can carry. V is the maximum payload volume of an aircraft. G is the maximum payload of the cargo plane.

$$D = \frac{G}{v} \tag{6}$$

4.4 Constraints on cargo packing

Due to the different types of cargo planes, the types of pallets may also vary, but they all meet the requirement that the total mass and volume of the cargo carried by the aircraft cannot exceed the total carrying capacity of all pallets. In order to make the model simpler, it is necessary to assume that all pallets used are of the same model, and all goods that need to be palletized can only be loaded into one pallet at most.

According to the requirements of the aircraft manual, each cabin has its corresponding maximum load, and the total mass of goods loaded on the pallet cannot exceed its maximum value. Therefore, the total weight and overall size of all goods loaded on a certain pallet must be less than or equal to the maximum capacity and load-bearing capacity of the pallet, as shown in equation (7). In addition, cargo planes also have their maximum load, so it is necessary to ensure that the overall weight of the cargo loaded in the cargo hold is lower than the maximum load capacity of the cargo hold. As shown in equation (8), W is the maximum load capacity of the cargo plane.

$$\begin{cases} \sum_{i=1}^{N} x_{ij} a_{ij} \le y_j A_j \\ \sum_{i=1}^{N} x_{ij} b_{ij} \le y_j B_j \\ \sum_{i=1} x_{ij} c_{ij} \le y_j C_j \end{cases} \tag{7}$$

$$\sum_{i=1} x_{ij} c_{ij} \le y_j C_j \tag{8}$$

4.5 Aircraft center of gravity constraint

The most basic condition for establishing the model in this thesis is that the cargo plane can fly smoothly, so it is necessary to consider the influence of the cargo plane's center of gravity. Due to differences in cargo loading positions and changes in fuel consumption, material delivery, ammunition launch, aerodynamic shape during flight, the center of gravity position may change. In all possible flight situations, the center of gravity position of the aircraft should be within the design allowable range. The front and rear limits of the center of gravity are the forwardmost and rearmost positions allowed by the aircraft's center of gravity during flight. As shown in Figure 4, F represents the aircraft lift, W_3 represents the empty aircraft weight, W_2 represents the fuel weight, W_1 represents the cargo weight, and x_1 represents the center of gravity position. It should be ensured that the center of gravity of the cargo plane is within the front and rear limits (a, b).

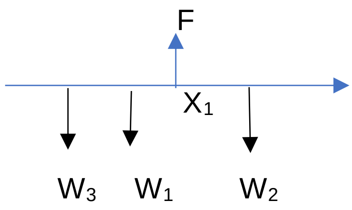

Figure 4 Aircraft Longitudinal Balance

For the sake of aircraft structure and flight safety, the bending moment of the aircraft body should be minimized as much as possible. Follow the principle of placing heavier goods close to the lifting point and placing lighter goods away from the lifting point. This is the most important principle and mechanical criterion in the loading optimization process.

4.6 Objective function

This thesis establishes corresponding constraints based on the characteristics of goods and containers, as well as the structure of cargo planes, considering weight issues. In order to maximize the efficiency of air cargo loading while ensuring safe loading and transportation, an objective function was established, as shown in equation (9). Among them, C_w and C_v are the return coefficients for heavy and light objects, both greater than 0.

$$O_1 = \sum_i I_i C_w w_i x_i + \sum_i (1 - I_i)\, C_v w_i x_i \qquad (9)$$

5 Empirical analysis section

In order to improve the efficiency of cargo loading, it is necessary to consider many factors to effectively save space and enable it to load more goods.

For example, in the case of midway unloading, goods arriving at the same location can be loaded as much as possible at once, which can minimize the situation of empty cargo planes or low loading efficiency. If it cannot be loaded at once and needs to be transported together with goods from other routes. We should consider whether there is a need for other goods to be transported to the final location after unloading midway, in order to improve the loading efficiency of the cargo plane as much as possible and reduce the phenomenon of empty holds. To improve loading efficiency, it is also possible to change the packaging of the goods and design appropriate box shapes so that they can load as many goods as possible. Improving loading efficiency not only depends on the space utilization of goods loaded on pallets, but also on the space utilization in each packaging box. If the packaging box is designed to be slightly larger than the length, width, and height of the unit cargo, minimizing the gaps in the packaging box can improve space utilization to a certain extent.

Of course, there are many ways to improve the utilization of cargo aircraft space, and there are more than just the two methods mentioned above. This thesis adopts two different methods to improve the utilization rate of cargo aircraft space. This thesis aims to optimize the total density of goods to be transported and the proportion of light and heavy goods to save space as much as possible. Although this method may not be suitable for loading urgent goods or goods with special requirements, for a batch of goods that need to be transported in advance without special requirements, it can save cargo space to a certain extent, allowing it to load more goods.

To verify the effectiveness of this model, this thesis will take DF Airlines' B747-8F all cargo aircraft as an example. Assuming there are a total of 133 batches of goods to be loaded, the total gross weight and total volume of these batches are 219470 kilograms and 42786 cubic feet, respectively.

5.1 The impact of DRHLG

Assuming that the volume and weight usage of PLTs are close to 100%, a portion of 133 batches of goods are combined and loaded to obtain the gross and volumetric weights of heavy goods and light goods in each case. Calculate the different density ratios of heavy and light goods in six different scenarios according to the formula, as shown in Table 3.

Table 3 Different density ratios of heavy and light goods

situations	GW^a (1)	VW^a (2)	GW^b (3)	VW^b (4)	DRHLG	CW (1+4)
1	79047	64440	30732	34524	1.38	113571
2	64718	46958	45282	52082	1.59	116800
3	69498	46580	40267	52510	1.95	122008
4	63335	35671	49520	63168	2.42	126503
5	73972	41976	36026	56989	2.79	130961
6	66862	32848	42769	66167	3.15	133029

The results show that the larger the DRHLG, the greater the weight that the cargo plane can load. In situations 5 and 6, it can be seen that when DRHLG reaches a certain value, the gross weight of the goods gradually stabilizes. From the table, it can be seen that from scenario 1 to scenario 6, the total gross weight increased by 17.1%. So DF Airlines can increase the billing weight of their cargo by loading more heavy cargo, thereby increasing overall revenue. Because freight is calculated based on the gross weight of heavy goods and the volume of light goods, and the weight and volume of these two types of goods are mutually balanced. (Note: GW represents gross weight, VW represents volumetric weight, and CW represents chargeable weight; unit: kg. a and b represent heavy and light goods, respectively.)

5.2 The impact of cargo density

To investigate the impact of different combinations of light and heavy goods on air freight charges. The DRHLGs of the goods used in this thesis are 2、2. 5、3. Analyze the relationship between the charging situation and the density of goods, as shown in Table 4.

Table 4 Different density ratios of heavy and light goods

situations	DRHLG = 3.0		DRHLG = 2.5		DRHLG = 2.0	
	density	CW	density	CW	density	CW
1	4.4	115985	4.4	114192	4.4	112305

2	4.7	120216	4.7	117176	4.7	114650
3	5.0	128238	5.0	122018	5.0	118777
4	5.2	131780	5.2	128548	5.2	123555
5	5.5	126861	5.5	125162	5.5	121495
6	5.8	126861	5.8	122485	5.8	118533

The results show that the charging situation for all three types of DRHLG is increasing. When the loading density is 5.2, the chargeable weight reaches its peak. Once the cargo density exceeds this value, the fee decreases as the density increases. The reason for this situation is that the density of cargo loaded on the cargo plane is lower than the optimal loading density of the cargo plane. This indicates that the cargo loaded by the cargo plane is very light, resulting in a far lower load-bearing capacity than the maximum load-bearing value. Although the weight of the cargo plane has not been reached, the loadable space of this cargo plane has been fully utilized, which will result in a decrease in air freight costs instead of an increase. Another scenario is when the density of cargo loaded on the cargo plane is higher than the optimal density. This will result in the cargo plane reaching its peak load capacity, but there is still a lot of space left, resulting in waste. This situation is also an unreasonable loading method.

The relationship between different loading densities and load-bearing capacity of DRHLG in three different scenarios is shown in Figure 5.

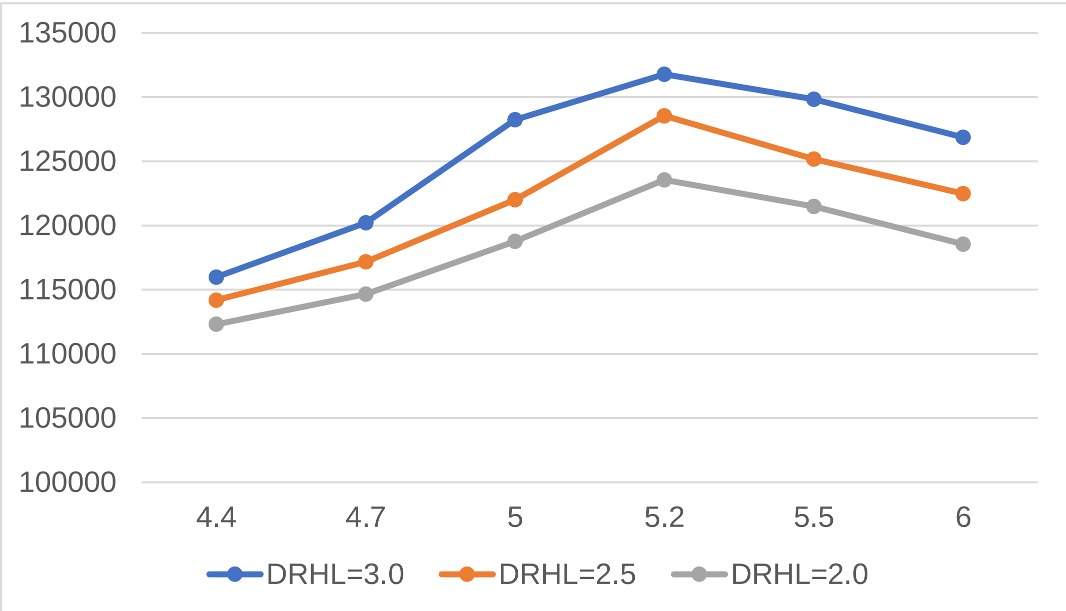

Figure 5 Relationship between DRHLG and load-bearing capacity

This figure indicates that under the same density of goods, if their DRHLG is higher, their billing weight is greater. It can be clearly seen from the figure that when the DRHLG is 3.0, it can carry more weight than the other two cases at the same density. So when DF Airlines assembles goods, they not only need to consider the impact of DRHLG, but also the optimal loading density of the goods, in order to maximize their chargeable weight and thereby increase the company's revenue.

5.3 Center of gravity constraint

In order to ensure smooth flight of the aircraft, this thesis assumes that the weight of goods on each pallet in the main cargo hold is m. B747-8F only considers the loading of the main cargo hold, and there are a total of 34 cargo holds in the main cargo hold that can be used to fix the pallets. Assuming the weight of the goods on pallet 1 is m_1, the weight of the goods on pallet 2 is m_2, and so on, the weight of the goods on pallet 34 is m_{34}, and $m_1 \geqslant m_2 \geqslant m_3 \geqslant \ldots\ldots \geqslant m_{34}$.

All goods should meet the following requirements: the height of the goods is less than the height of the cargo hold. The mass of each group of goods is less than the maximum weight carried by a single container. The mass of all goods is less than the maximum weight carried by the cargo plane. Determine the number of loading columns based on factors such as the size of the aircraft cargo hold and the volume of transported goods, and arrange the goods in descending order of weight. Then, based on the number of loading columns, each N pallet is divided into a group, where N represents the number of loading columns for the goods. For example, when N=2, the first group (m_1/m_2), the second group (m_3/m_4), and the third group (m_5/m_6); When N=3: Group 1 ($m_1/m_2/m_3$), Group 2 ($m_4/m_5/m_6$), Group 3 ($m_7/m_8/m_9$) ... When loading, arrange the cargo in order of weight from heavy to light. Generally, there are two columns on cargo planes, so every two pallets with similar weight are divided into a group, and the pallets are numbered and grouped as shown in Table 5.

Table 5 Classification of Goods

Group number	1	2	3	4	5	6	7
goods	m_1, m_2	m_3, m_4	m_5, m_6	m_7, m_8	m_9, m_{10}	m_{11}, m_{12}	m_{13}, m_{14}
Group number	8	9	10	11	12	13	14

goods	m_{15}, m_{16}	m_{17}, m_{18}	m_{19}, m_{20}	m_{21}, m_{22}	m_{23}、m_{24}	m_{25}, m_{26}	m_{27}, m_{28}
Group number	15	16	17				
goods	m_{29}, m_{30}	m_{31}, m_{32}	m_{33}, m_{34}				

In the longitudinal direction, it is necessary to consider the aircraft's flight maneuverability and stability. When planning the loading layout, for the sake of aircraft structure and flight safety, the bending moment of the aircraft should be minimized as much as possible, that is, the pitch balance of the aircraft. Generally, the principle of placing heavier goods close to the lifting point and placing lighter goods away from the lifting point is followed. In fact, the entire wing will provide lift, and the calculated center of gravity of the cargo is located within the average aerodynamic chord. The loading method of the goods obtained through this arrangement and combination follows the principle of minimizing bending moments, so it can be assumed that the center of gravity of the goods coincides with the lifting point.

To ensure that the final loading center of gravity is within the front and rear limits of the center of gravity, assemble from d_0 (i.e. the distance between the center of gravity of the first group of goods and point O) in the order of group numbers from small to large. The loading sequence is shown in Figure 6.

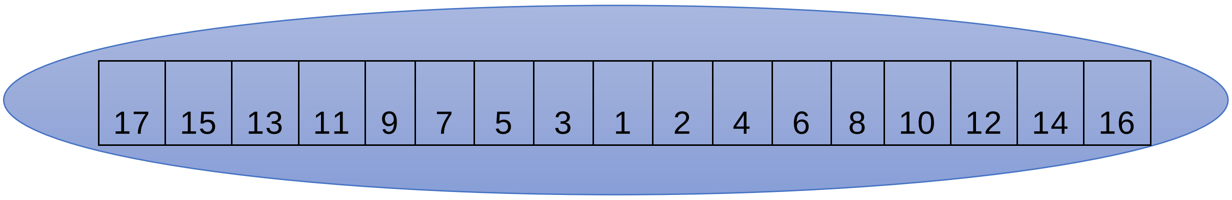

Figure 6 Cargo Loading Sequence

In the horizontal direction, the moment of the cargo on the aircraft's central axis determines the rolling balance during flight and the force balance of the landing gear on the ground. A smaller torque can reduce the torque applied to the body, and during the loading process, it should be minimized as much as possible. Implementing multiple rows of loading in the cabin, taking into account the torque effect of the arrival weight on the local and overall fuselage, will result in more complex loading. In practice, dual column loading is the most common.

Taking this as an example, this thesis analyzes the loading layout of cargo planes with one column being A and the other column being B. However, this analysis method is also applicable to the case of multi column loading. In normal cargo loading, the cargo is usually loaded from the closest position to the center of gravity in descending order of weight. Calculate the moment M_A and M_B of the weight of the goods on both sides against the longitudinal axis for each group of goods loaded. If $M_A \geqslant M_B$, when loading the next group of goods, place the heavier ones on side B and the lighter ones on side A. Follow this method to cycle until the loading is completed. At this point, the wing needs to provide less torque to ensure its stable flight.

6 Case analysis

In this chapter, specific data will be described, with the fully loaded B747-8F as the target, and the cargo in each compartment will be reasonably allocated based on the center of gravity, so that the cargo plane can fly smoothly.

6.1 Loading and Center of Gravity Analysis of B747-8F

According to DF Airlines' previous loading methods based on manual experience, it was not possible to achieve the optimal loading effect for individual pallets in each cabin, and it was not possible to strictly control the loading density of each cabin and the proportion of light and heavy cargo. Take these 133 batches of goods as an example. Through consulting with the freight manager of DF Airlines, it was learned that according to DF Airlines' loading method, to transport this batch of goods, a fully loaded B747-8F cargo plane and an underloaded cargo plane will be used. 22 cabins will be used for loading on cargo planes that are not fully loaded, but after changing the loading method using the method described in this thesis, only 21 cabins are needed on cargo planes that are not fully loaded. It is worth noting that the chargeable weight of these 133 batches of goods has not changed, because the chargeable weight of this batch of goods always equals the gross weight of heavy goods plus the volume weight of light goods, and this batch of goods has not increased or decreased, so the chargeable weight of this batch of goods has not changed. The only change is the utilization of cargo aircraft space, which saves one space to load other cargo in an underloaded cargo aircraft.

Furthermore, according to the constraints of the center of gravity, the goods assembled according to the method described in this thesis will be loaded into the cargo plane. Due to the need for two cargo planes for loading, this thesis takes a fully loaded cargo plane as the analysis objective for ease of explanation. Assuming the distance between goods is d=0.2m, the length and width of each pallet are both 2m. The weight of each cargo is sorted in descending order as shown in Table 6.

Table 6 Goods Number and Weight

goods	1	2	3	4	5	6	7
weight/kg	4097	4053	4052	4041	4032	4031	4029
goods	8	9	10	11	12	13	14

weight /kg	4027	4019	4018	4011	4009	3954	3935
goods	15	16	17	18	19	20	21
weight /kg	3933	3932	3921	3915	3911	3907	3889
goods	22	23	24	25	26	27	28
weight /kg	3884	3883	3877	3876	3873	3871	3869
goods	29	30	31	32	33	34	
weight /kg	3866	3864	3861	3858	3856	3837	

For the loading task, the B747-8F cargo plane is divided into two columns. Divide every 2 pallets with similar weights into one group, as shown in Table 7.

Table 7 Classification of Goods

Group number	1	2	3	4	5	6	7
Goods number	1、2	3、4	5、6	7、8	9、10	11、12	13、14
weight /kg	8150	8093	8063	8056	8037	8020	7889
Group number	8	9	10	11	12	13	14
Goods number	15、16	17、18	19、20	21、22	23、24	25、26	27、28
weight /kg	7865	7836	7818	7773	7760	7749	7740
Group number	15	16	17				
Goods number	29、30	31、32	33、34				
weight /kg	7730	7719	7693				

Under the constraint of the center of gravity, following the principle of placing heavier goods near the lifting point and lighter goods far from the lifting point, the distribution of goods in the longitudinal direction is shown in Figure 7.

17	15	13	11	9	7	5	3	1	2	4	6	8	10	12	14	16

Figure 7 Longitudinal Loading Layout of Cargo Aircraft

Horizontally, one column of the shilling is A and the other column is B. First, place the first group of goods at position one in Figure 4.1. If cargo 1 is placed on side A, then cargo 2 is placed on side B. Then calculate the moment between the weight of the goods on both sides and the longitudinal axis. At this time, M_A=8030.12, M_B=7943.88, $M_A>M_B$, then when loading the next group of goods, cargo 3 should be placed on side B and cargo 4 should be placed on side A. At this point, calculate the torque on both sides again, M_{A1}=15950.48, M_{B2}=15885.8, $M_{A1}>M_{B2}$, so cargo 5 should be placed on side B, cargo 6 should be placed on side A, and so on. The final loading result is shown in Figure 8.

A	33	29	26	21	17	14	9	6	1	4	8	11	15	19	23	28	32
B	34	30	25	22	18	13	10	5	2	3	7	12	16	20	24	27	31

Figure 8 Layout of cargo plane lateral loading

At this point, the wing needs to provide less torque to ensure stable flight of the cargo plane. This is also the lateral balance of the cargo plane.

7 Conclusion

This chapter mainly includes a summary of the discussion of the results of this thesis and a summary of my own experiences.

7.1 Thesis summary

This thesis focuses on the research of cargo allocation problems based on center of gravity constraints in air cargo transportation. The main purpose of this thesis is to adjust the proportion of heavy and light cargo loaded by cargo planes and the optimal loading density of goods under the constraint of the center of gravity. To achieve the goal of improving the utilization of cargo aircraft space and load as much cargo as possible. This thesis is based on DF Airlines' cargo planes and their pending cargo lists, and verifies the experimental calculation results. The following two conclusions are drawn.

Firstly, under the condition of fully utilizing loadable space and payload, the loadable weight increases with the increase of DRHLG. When DRHLG reaches a certain level, the degree of weight increase tends to stabilize. This indicates that airlines can adjust the combination of heavy cargo with higher density and light cargo with lower density on the same flight to save space for cargo planes.

Secondly, when the average cargo density loaded on a flight approaches the optimal loading density for that flight, the chargeable weight will increase. Therefore, airlines should control the average cargo density to approach the optimal loading density, and increase the utilization of cargo space by adjusting the ratio between light and heavy cargo.

The method in this thesis can enable cargo planes to determine the percentage of cargo with different densities by referring to the optimal loading density under stable flight and structural constraints, and load as much cargo as possible. This improvement allows the cargo plane to use the saved space to continue loading other goods, thereby increasing the total transportation revenue.

7.2 Gains and reflections

This thesis delves into the optimization problem of aircraft loading and proposes targeted optimization strategies by analyzing the loading problem of B747-8F cargo plane cargo loading space utilization. It has been found that optimizing the proportion of light and heavy cargo and the overall cargo density can improve the utilization rate of cargo aircraft space. The implementation of this optimization strategy can increase the loading rate of FD Cargo Airlines' B747-8F cargo aircraft, thereby enhancing the airline's revenue.

However, due to the limited theoretical knowledge and professional level of the author, many situations related to practical problems cannot be fully considered. In the process of analyzing problems, there are still many qualitative problems that cannot be converted into quantitative problems for analysis. In addition, due to the particularity and complexity of aircraft loading issues, many studies still need to be improved and perfected. The research content that needs further improvement in the future is mainly reflected in the assumptions in this thesis, which assume that the type of goods is regular rectangular goods, and the cargo hold is also assumed to be regular containers, without considering irregular goods and cargo holds. The purpose of doing so is to facilitate calculations, and further research is needed on the loading of irregular cargo and irregular containers in air cargo in the future. Moreover, the constraints considered in this thesis are limited and cannot be considered completely. In future research, it is necessary to consider comprehensively in order to make the research problem more in line with the actual aircraft loading problem.

The biggest gain in writing this thesis was the theoretical framework. Because this theoretical framework is different from the form required by our school, it requires us to study diligently, read and accumulate a large amount of literature, take good notes of it, and learn to summarize and organize literature. The biggest challenge in this thesis is choosing the direction to study. Because this topic must be related to both aviation and logistics, and it is also necessary to keep up with changes in the times and choose research directions that meet the requirements. And the direction chosen should be specific, not a general direction, as it can easily magnify our's ignorance. The most important aspect in this thesis is the ability to think logically. First identify the problem, then propose a method, and then solve the problem. It requires a logical framework for the entire thesis, as well as every paragraph and sentence. The logical framework of a thesis reflects its logical nature. To write a good thesis, logical thinking is essential.

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