ORCID ID: 0009-0003-4551-7476

AIRLINE PLANNING AND SCHEDULING

A DISSERTATION

SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE AWARD OF THE DEGREE

OF

MASTER OF SCIENCE

IN

MATHEMATICS

Submitted by:

JYOTI MISHRA
2K21/MSCMAT/25
jyotimishra_2k21mscmat25@dtu.ac.in

UJJWAL KAUSHIK
2K21/MSCMAT/53
ujjwalkaushik_2k21mscmat53@dtu.ac.in

Under the supervision of

Prof. L N Das
lndas@dce.ac.in

DEPARTMENT OF MATHEMATICS

DELHI TECHNOLOGICAL UNIVERSITY

(Formerly Delhi College of Engineering)

Bawana Road, Delhi-110042, India

ORCID ID: 0009-0003-4551-7476

DELHI TECHNOLOGICAL UNIVERSITY

(Formerly Delhi College of Engineering)

Bawana Road, Delhi – 110042

CANDIDATES'S DECLARATION

We, **Jyoti Mishra (2K21/MSCMAT/25) and Ujjwal Kaushik (2K21/MSCMAT/53),** students of M.Sc. (Mathematics) hereby declare that the project Dissertation titled "AIRLINE PLANNING AND SCHEDULING" which is submitted by us to the Department of Applied Mathematics, Delhi Technological University, Delhi in partial fulfillment of the requirement for the award of the degree of Masters of Science, is original and not copied from any source without proper citation. This work has not previously formed the basis for the award of any degree, diploma, fellowship or other similar title or recognition.

Place: Delhi

Date: 20-05-2023

Jyoti Mishra

(2K21/MSCMAT/25)

Ujjwal Kaushik

(2K21/MSCMAT/53)

ORCID ID: 0009-0003-4551-7476

DELHI TECHNOLOGICAL UNIVERSITY

(Formerly Delhi College of Engineering)

Bawana Road, Delhi – 110042

CERTIFICATE

I hereby certify that the Project Dissertation titled AIRLINE PLANNING AND SCHEDULING which is submitted by **Jyoti Mishra (2K21/MSCMAT/25)** and **Ujjwal Kaushik (2K21/MSCMAT/53)**, Department of Applied Mathematics, Delhi Technological University, Delhi in partial fulfillment of the requirement for the award of the degree of Masters of Science, is a record of the project work carried out by the students under my supervision. To the best of my knowledge this work has not been submitted in part of full for any degree or diploma to this university or elsewhere.

Place: Delhi

Date: 20-05-23

Prof. L.N Das

Mentor

Professor

Department of Applied Mathematics

ORCID ID: 0009-0003-4551-7476

ACKNOWLEDGEMENT

The successful culmination of any task would be incomplete without giving due acknowledgement to the people who made it possible and without whose constant guidance and encouragement, the project would not have been successful.

We would like to firstly thank our project guide, Prof. LN. Das, without whose motivation and guidance the completion of this project would not have been possible. It was only through constant communication and reporting to him that this project had a clear direction and milestones to be accomplished

We would also like to take this moment to show our sense of gratitude to one and all, who indirectly or directly have lent us their hand in this task. We feel happy and content, in expressing our deep sense of gratitude to all those who have helped us in presenting this project.

Last, but never the least, we thank our parents for always being with us, in every Sense.

ORCID ID: 0009-0003-4551-7476

STATEMENTS AND DECLARATIONS

Funding

The authors declare that no funds, grants, or other support were received during the preparation of this manuscript.

Competing Interests

The authors have no relevant financial or non-financial interests to disclose.

Author Contributions

Material preparation, data collection and analysis were performed by Prof. L.N Das, Jyoti Mishra and Ujjwal Kaushik. All authors commented on previous versions of the manuscript and made substantial contributions to the conception of the work, analysis and interpretation of data.

We drafted the work and revised it critically for important intellectual content.

Prof. L.N Das, Jyoti Mishra and Ujjwal Kaushik approved the version to be published and agree to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

ORCID ID: 0009-0003-4551-7476

ABSTRACT:

Efficient crew scheduling plays a vital role in ensuring smooth operations and optimal resource utilization within the airline industry. This report presents a comprehensive analysis of crew scheduling using the Hungarian method, a powerful technique derived from operations research. The objective of this study is to develop a systematic approach for assigning crew members to flights, considering various constraints such as crew availability, qualifications, and legal regulations.

The report begins by providing an overview of the crew scheduling problem, emphasizing its complexity due to the large number of flights, crew members, and intricate interdependencies. It then introduces the Hungarian method as a suitable mathematical framework for optimizing crew assignments, leveraging its ability to solve assignment problems in polynomial time.

Next, the report outlines the implementation of the Hungarian method in the context of crew scheduling. It explains the process of formulating the problem as an assignment matrix.

To evaluate the performance of the Hungarian method, the report presents a case study involving a medium-sized airline. Real-world data, including flight schedules, crew availability, and legal regulations, are utilized to demonstrate the effectiveness of the proposed approach. The results show significant improvements in crew utilization and operational efficiency compared to traditional manual scheduling methods.

In conclusion, the application of the Hungarian method in crew scheduling proves to be a valuable tool for airlines, enabling them to optimize crew assignments while considering multiple constraints.

Keywords: integer programming, objectives, Constraints, Operational Requirements, Assignment Problem, Hungarian Method

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LITERATURE REVIEW

Crew scheduling is a critical aspect of operations in the aviation industry, requiring efficient allocation of crew members to flights while considering various constraints. Over the years, operations research techniques have played a crucial role in optimizing crew scheduling processes. This literature review provides an overview of key studies that have utilized operations research methods to address crew scheduling challenges.

One significant area of research in crew scheduling involves mathematical programming models. These models aim to find optimal crew assignments that minimize costs, maximize crew utilization, and adhere to regulatory requirements. Studies by Chen et al. (2008) and Wang and Chen (2012) demonstrate the application of integer programming and mixed-integer programming models, respectively, to solve crew scheduling problems. These models consider factors such as crew availability, qualifications, preferences, and legal regulations to generate optimal crew schedules.

Another approach within operations research is the use of metaheuristic algorithms for crew scheduling. Metaheuristic algorithms, such as genetic algorithms, simulated annealing, and tabu search, provide effective solutions for large-scale crew scheduling problems. Studies by Miranda-Moreno and Hickman (2007) and Nguyen et al. (2014) explore the application of genetic algorithms to crew scheduling optimization. These approaches introduce randomness and search techniques to find near-optimal crew schedules within reasonable computational time.

Crew scheduling models have witnessed a rising interest in incorporating uncertainty and disruptions in recent years. Stochastic programming and robust optimization techniques have been employed to account for uncertainties in crew availability, flight delays, and disruptions. Studies by Jia et al. (2017) and Lee et al. (2020) incorporate stochastic programming models to optimize crew assignments considering uncertain parameters, providing more robust schedules that can adapt to unexpected events.

Additionally, crew pairing optimization, which involves grouping flights into efficient sequences or pairings, has been extensively studied. Crew pairing algorithms aim to reduce crew deadhead (non-revenue) travel time and improve crew productivity. Studies by Desaulniers et al. (2010) and Aulbach et al. (2012) introduce efficient algorithms for crew pairing optimization, which consider pairing constraints, flight connections, and other operational requirements.

Furthermore, the integration of crew preferences and satisfaction into crew scheduling models has gained attention. Researchers have incorporated crew preferences for specific routes, home bases, and rest periods, aiming to improve crew satisfaction and reduce turnover. Studies by Tavakkoli-Moghaddam et al. (2013) and Saharidis et al. (2016) demonstrate the consideration of crew preferences in crew scheduling models using mathematical programming techniques, leading to more desirable crew schedules.

In conclusion, operations research methods have played a significant role in crew scheduling optimization. Mathematical programming models, metaheuristic algorithms, stochastic programming, robust optimization, and crew pairing optimization have been employed to tackle various aspects of crew scheduling challenges. Integrating crew preferences and addressing uncertainty further enhance the effectiveness and robustness of crew scheduling models. These studies collectively contribute to the body of knowledge in crew scheduling optimization and offer valuable insights for improving crew scheduling practices in the aviation industry.

INTRODUCTION

The airline's scheduling process aims to develop a strategy for effectively utilizing its resources, including aircraft, to meet projected demand.

Flight planning and operations serve as the initial stages of any airline's planning and operations. The flight schedule acts as a timeline that specifies the destinations and timings of flights. The decision to operate a specific flight is influenced by factors such as market demand forecasts, aircraft capabilities, labor availability, regulations, and the behavior of competing airlines. The number of airports served and flight frequencies are often used as indicators to gauge the size and coverage of an airline's network.

In large airlines, the route development and flight scheduling teams may consist of over 30 professionals. A sample of Airline X's daily flight schedule for select flights is provided in Table 1. Prior to the 1978 Airline Deregulation Act, airlines were obliged to follow the prescribed flight paths set by the Civil Aeronautics Board (CAB), regardless of customer demand. During that era, most carriers prioritized long point-to-point flights. However, the deregulation of the aviation industry has granted airlines the freedom to choose their served markets and flight frequencies. As a result of this shift, many airlines have fundamentally altered their routing strategies away from point-to-point flights.

Table 1: Sample timetable

Carrier	Depart		Arrive	
Flight No	Time	Airport	Time	Airport
X123	7:20 AM	DEL	10:00 AM	GOI
X456	7:25 AM	HYD	9:55 AM	DEL
X789	9:55 AM	DEL	12:15 AM	HYD
X134	4:35 PM	BOM	7:00 PM	DEL
X145	5:45 PM	BOM	6:45 PM	GOI

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The airline product can be influenced by several key factors, including in-flight amenities, seating arrangements, scheduling, and pricing strategies. When developing their timetables, airlines aim to anticipate the demand for their offerings during a specific timeframe. The schedule planning process is designed to address a variety of conflicting objectives. Timetable creators often need to navigate internal and external constraints simultaneously. As the planning cycle for schedules commences, airlines must prepare their schedules well in advance, typically six to nine months prior to a specific season. During this time, they may need to devise unique route patterns that align with their goals, operational plans, and existing schedules.

Objectives for Scheduling

The scheduling goals comprise:

I. Customer satisfaction

II. Human resource productivity

III. High aircraft utilization

IV. High load factors

V. High frequency

VI. Maximization of Connections

Customer Satisfaction

The design of the airline's schedule should take into consideration the specific requirements of the different market segments it aims to serve. This is an essential aspect of the schedule planning process. To achieve this, timetable designers rely on information about passenger behavior. Such data can be gathered from various sources, including historical records from the yield management division, insights shared by sales and reservation staff, and market research conducted by the airline's marketing department. By incorporating this information, the scheduler can effectively consider the preferences, needs, and desires of the passengers when constructing the schedule.

Human resource productivity

The planners of schedules must make sure that staffing levels are optimal for each shift. They want to lessen the highs/ups and lows/ down in staffing needs so an airline can give a consistent level of service. The well-prepared scheduling strategy will lead to lower staffing expenditures. Although there is little or no work for the extra workers to complete during their assigned shifts on weekends or holidays, they will typically receive additional allowances. However, it's possible that the operational and technical sectors will always need a minimal amount of persons for each shift.

High Aircraft Utilization

One crucial things to keep in mind when using aircraft is , they can only be profitable while in flight. The corporation loses money when an aircraft is on ground. Assuming the indirect costs of owning an aero plane (depreciation, interest, etc.) are largely constant is one approach to look at this. Consequently, the overall hourly indirect expenses fall as aircraft utilization improves. As the result, overall expenses go down, which improves the airline's financial standing overall.

The utilization of an airline's aircraft is heavily influenced by its route network. Different airlines have varying levels of aircraft utilization. If an airline's route network is dominated by long-haul flights, it tends to achieve high aircraft utilization rates. Conversely, shorter flights result in longer turnaround times, leading to decreased overall aircraft availability.

Typically, long-haul airlines have longer average daily aircraft utilization, with around 12-13 hours of flight time per day or 4,250 hours annually. In contrast, short-haul airlines average around 7.5 hours per day or 7,250 hours annually. However, certain short-haul airlines, particularly low-cost carriers, operate for 8 to 9 hours per day or approximately 3,300 hours annually.

The role of schedule planners is to design schedules that maximize aircraft utilization for their specific routes.

High Load Factors

The scheduling plan aims to optimize the utilization of available capacity and traffic within a given timeframe. It is crucial for an airline to strike the right balance between operating flights too frequently and the risk of incurring financial losses. If an airline operates an excessive number of flights on a specific route due to an inaccurate schedule estimation, it may result in planes taking off with empty seats, leading to financial losses for the airline. Therefore, careful planning of the load factor is essential, ensuring that it is neither set too high nor too low, to maximize profitability and operational efficiency.

High Frequency

Increasing the frequency of flights to specific destinations has proven to be a successful strategy for numerous airlines, leading to an expansion of their market shares or even establishing them as market leaders. Industry analysts have consistently demonstrated that airlines experience a boost in market share and competitive advantage by enhancing the frequency of flights to targeted areas.

Maximization of Connections

Airlines strategically design their flight itineraries to optimize passenger connections at both the origin and destination of a specific route. Many carriers have established connecting hubs with the primary goal of creating additional points for passenger traffic to converge and disperse for long-haul flights.

Consistent Timings

Maintaining consistent flight departure times for specific services from season to season, also known as "clockface timing," is an important aspect of scheduling. By striving for consistency, airlines aim to foster familiarity and customer loyalty. However, achieving this regularity may pose challenges due to certain scheduling restrictions, which will be explained shortly.

Scheduling Restrictions

Scheduling restrictions can be divided into two categories.

A. External restrictions

- Slot issues
- Night curfews
- Rules for the Industry
- Pool agreements
- Peak additional fees.

B. Internal Constraints

- Maintenance requirements
- Standby arrangements
- General operational requirements

We will discuss one by one the scheduling constraints.

External Constraints

Slot issues

Congestion issues are becoming more prevalent in many airports. Certain airports may frequently see more aviation traffic than their runways can handle. In addition to London Heathrow, Tokyo Narita, Washington National, Frankfurt, and Milan Linate, these problems exist there as well. The effect is that the air traffic controllers are now compelled to employ a slot system, in which arrival and departure times are given time slots. Such the system functions according to a set of principles.

The principle of "grandfather rights" represents the most foundational concept among these ideas. It stipulates that a carrier will retain the privilege to utilize a specific slot in a future equivalent season if it had already utilized that slot in a specific prior season. This strategy has worked well for existing carriers. To adjust timings or boost frequencies at crowded airports, however, could place significant restrictions on the schedule planners.

Night Curfews

During nighttime hours or specific periods, numerous airports either cease operations or function at significantly reduced capacity. For the fact that aircraft must be scheduled to and from such airports during daylight hours, night curfews impose limits on schedule planners. These kinds of time limits are typically implemented at airports where powerful, local environmental groups are active in lobbying. Any airline that violates the rules for the nighttime curfew is typically punished severely.

Rules for the Industry

Governments may occasionally give more airlines the sole right to operate on specific routes. A certain point or points could be used for economic, touristic, or other objectives. These rules could be seen as yet another type of constraint, and they might have a impact on how schedules are made.

Pool Agreements / Joint Venture Agreements

In different fields, airlines occasionally engage in joint venture arrangements. However, the agreements pertaining to frequency, equipment type, and timings have effect on how the airlines design their schedules.

Peak additional fees

Airports with serious congestion issues may implement particular remedies. Peak surcharges are typically levied to travelers and flying during particular peak hours. They are framed to deter airlines from operating at busy, peak times. These precautions could not be particularly effective because there are so many other factors that could affect or even determine when flights take place. Peak surcharges can occasionally exacerbate congestion issues, especially during peak hours, by adding new, more severe peaks before and after the initial high periods.

Internal Constraints

Maintenance Requirements

The planners need to consult the engineering department as aircraft maintenance requirements significantly impact scheduling. Each aircraft in the airline's fleet has its unique maintenance schedule, which includes various inspections conducted at different times. The schedule planners must be aware of the maintenance periods when the aircraft will be on the ground. Before the necessary maintenance checks can take place, a sufficient amount of aircraft time needs to be "blocked off" from the overall fleet availability. Therefore, the schedule must account for the allocated maintenance times.

Standby Arrangements

The schedule planners face the challenge of striking a balance between the airline's need for operational efficiency and their goal of adhering to the timetable. It is essential for the schedule creators to ensure that their services are reliable and punctual when designing the schedule. While this may seem straightforward in theory, it can be more complicated in practice. Despite the schedule planners' expertise in crafting feasible schedules, unforeseen circumstances such as aircraft delays can still occur. Factors like unexpected issues, inclement weather, air traffic control, connecting passengers, and other variables can all contribute to delays.

The airline must be prepared to handle such unforeseen situations when they arise. Schedule planners may utilize specialized tools to forecast future performance by analyzing historical timetables and punctuality data. Some airlines may have contingency plans in place to address delays and maintain schedule timeliness. This could involve designating a specific aircraft to serve as a backup for the rest of the fleet. The extent of standby coverage required by an airline can vary based on several factors, including the airline's financial situation, the age and condition of its fleet, the competitive environment, and more.

General Operational Requirements

When designing schedules, various general operating criteria need to be considered. These may include turnaround times, crew breaks and lunches, aircraft cleaning and catering services, among other operational needs. Schedule planners typically create two schedules per year, one for the summer season and one for the winter season. The scheduling cycle usually begins nine months prior to the start of the respective season. While specialized systems may be employed by different airlines, the process generally involves the following steps:

a) The airline's fleet of aircraft is sequentially assigned to specific routes throughout the day.

b) This assignment process is repeated multiple times, resulting in the allocation of each aircraft to a particular route for each day of the week.

c) The information generated from steps (a) and (b) provides a comprehensive overview of tasks for each aircraft. This information is consolidated in an aircraft integration chart.

d) Once the integration chart is finalized, copies are distributed to all operational regions impacted by it, and these regions provide their feedback on the chart.

e) The integration chart serves as an operational document and is not directly relevant to the airline's business units such as sales and marketing. Consequently, a draft timetable is created, incorporating the data from the integration chart but presenting it in a different format. This draft timetable is distributed within the airline's commercial regions simultaneously with the integration chart distribution in the operational areas. The commercial regions also provide feedback on the commercial elements of the draft timetable.

f) Following the distribution of the integration chart and draft timetable, meetings are held between the operational and commercial sections to discuss and align the schedules. For example, the marketing departments ensure that the final schedule aligns with their objectives.

The schedule planners make adjustments and refinements to the draft schedules based on feedback received from different departments. Subsequent drafts are sent out for review, and the final drafts contain the airline's schedules for the specific season.

Airline’s number (airline fleet size) in India

In India, there are currently 39 operational airlines, encompassing scheduled, regional, chartered, and cargo carriers. The scheduled airlines hold the dominant position in the domestic market and are responsible for a significant share of it. Among these scheduled airlines, a majority operate in the budget segment, with popular names like Vistara, Indigo, GoAir (now known as Go First), and SpiceJet leading the way.

Fig. 1: Airports Authority of India manages a total of 137 airports, comprising 103 domestic airports, 24 international airports, and 10 airports designated for customs operations.

Flight-Scheduling Process

The size of the airline's fleet imposes constraints on the scheduling process. The schedule planners must ensure that the appropriate number of aircraft is scheduled across the airline's network in a manner that aligns with the company's overarching goals. Once the scheduling planning process is complete and the final schedule is established, the plan is presented to the operational divisions within the airline.

The implementation of the schedule is then their duty. As a result, the planning of schedules is essential to the efficient operation of any airline. It influences other departments' considerations and is influenced by them.

It is impossible to overstate the value of the timetable plan. The plan must be as precise as possible because the airline cannot ever underestimate or overestimate the needs of its fleet. The airline won't book enough flights and won't be able to run the flights that target consumers are requesting if it underestimates the fleet's needs.

As an alternative, if the airline overestimates the need for its fleet, it would likely schedule too many flights, underutilizing its fleet. The airline will ultimately suffer huge financial losses as a result of this. For these reasons, other departments should constantly collaborate with the scheduling department.

The involvement of various airline departments in the scheduling processes is crucial for enhancing overall operations. Departments such as corporate planning, fleet planning, sales, marketing, product development, operations control, catering, cargo, ground operations, and staff recruitment should all participate in the scheduling decisions. By actively engaging these departments, the airline can ensure that the schedule not only meets but exceeds the customer's needs, with the marketing division playing a vital role in this regard.

Route Development

Route development initiatives can be categorized into two types: tactical and strategic. Strategic planning focuses on future schedules, ranging from a few months to as long as 10 years, depending on airline policies. It addresses major changes in the business and operational environments through long-term developments. On the other hand, tactical plans concentrate on quick adjustments to the timetable and routes, often on a daily basis. This involves closely monitoring markets, competitors, and operations. The tactical plan involves adding, removing, and modifying city-pair markets and flight frequencies. In the following section, we will briefly outline the phases of creating a flight schedule and discuss the decisions made at each stage.

Table 2: Maintenance Schedule

60+ MONTHS	36 – 12 MONTHS	12 – 3 MONTHS	4 – 1 MONTHS
Long Range Planning	Market Evaluations	Schedule Optimization	Schedule Issues

Long-range planning, which spans over 60+ months, involves market evaluations and strategic considerations. Within the 36 to 12-month timeframe, schedule optimization takes place to fine-tune the flight schedule. As the timeline narrows down to 12 to 3 months, focus shifts towards addressing schedule issues and making necessary adjustments. Finally, in the 4 to 1-month timeframe, the schedule is closely monitored and further optimized to ensure efficient operations.

Long-Range Schedule Planning

1. Diversifying the fleet to ensure variety

2. Planning manpower requirements

3. Safeguarding and maintaining the efficiency of hubs

4. Considering the addition or alteration of hubs

5. Ensuring adequate facilities at airports

Market Evaluations

1. Assessing frequency and timing of service for each market

2. Identifying potential new markets and discontinuing existing ones

3. Establishing pricing policies

4. Anticipating competitors' actions and behaviors

5. Exploring code-sharing agreements and alliances

Schedule Optimization

1. Developing the initial schedule based on available fleet resources

2. Assigning appropriate aircraft to flights

3. Evaluating the capabilities of facilities and workforce

Schedule Issues

1. Addressing crew-related challenges

2. Managing arrival times

3. Managing departure times

4. Handling maintenance-related matters

Assignment Problem

The objective of this specific linear programming problem (LPP) is to determine the optimal allocation of multiple tasks (jobs) among an equal number of facilities (persons). In this scenario, it is assumed that each person is capable of performing each task, but with varying degrees of efficiency. For example, a department head may have 4 individuals available for assignment and 4 positions to be filled. The primary goal is to identify the most suitable assignment that aligns with the department's requirements.

General form of an Assignment Problem:

The assignment problem can be expressed using a cost-effectiveness matrix, denoted as an $n \times n$ matrix [cij], where each element represents the cost of assigning the i^{th} person (facility) to the j^{th} task (work).

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Persons \ Jobs	1	2	3	....	j	....	n
1	c_{11}	c_{12}	c_{13}	....	c_{ij}	....	c_{in}
2	c_{21}	c_{22}	c_{23}	....	c_{2j}	....	c_{2n}
3	c_{31}	c_{32}	c_{33}	....	c_{3j}	....	c_{3n}
....	....	....	....	....	....	....	....
i	c_{i1}	c_{i2}	c_{i3}	....	c_{ij}	....	c_{in}
......	....	....	....	....	....	....	....
n	c_{n1}	c_{n2}	c_{n3}	....	c_{nj}	....	c_{nn}

Fig. 2: Matrix for Assignment Problem

Mathematical Formulation:

The assignment problem can be mathematically formulated as follows:

$$z = \sum_{i=1}^{n} \sum_{j=1}^{n} C_{ij} x_{ij}$$

$$where\ x_{ij} = \begin{cases} 1, & if\ i'th\ person\ is\ assigned\ to\ the\ j'th\ job \\ 0, & if\ i'th\ person\ is\ not\ assigned\ to\ the\ j'th\ job \end{cases}$$

as per the conditions:

$\sum_{i=1}^{n} x_{ij}$ = *1, j=1,2 … n.*

This implies that the i^{th} person can only perform one job., i=1,2,......,n.

$\sum_{j=1}^{n} x_{ij} = 1$, i=1,2 … n.

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This indicates that the j^{th} job should be assigned to only one person, j=1,2,......,n.

Algorithm used: Munkres

```
In [37]: from munkres import Munkres, print_matrix

         matrix = [[20, 19, 6.5,9],
                   [22, 21, 15.5,9],
                   [17.5,18.5,20,15.5],
                  [8.5,7.5,18,21.5]]
         m = Munkres()
         indexes = m.compute(matrix)
         print_matrix(matrix, msg='Lowest cost through this matrix:')
         total = 0
         for row, column in indexes:
             value = matrix[row][column]
             total += value
             print(f'({row}, {column}) -> {value}')
         print(f'total cost: {total}')

         Lowest cost through this matrix:
         [  20,   19,  6.5,    9]
         [  22,   21, 15.5,    9]
         [17.5, 18.5,   20, 15.5]
         [ 8.5,  7.5,   18, 21.5]
         (0, 2) -> 6.5
         (1, 3) -> 9
         (2, 0) -> 17.5
         (3, 1) -> 7.5
         total cost: 40.5
```

Figure 3: Applying Munkres on sample data set

Scheduling problem

Every mode of transportation has a set number of vehicles that go between two cities or locations. For instance, a flight with the number 102 departs from Delhi, arrives in Dehradun, and then, once the requisite amount of time has passed, departs from Dehradun for Delhi with the number 201.

The time allotted for crew to relax before departure is known as the layover period. Our challenge is to schedule a small number of crewed aircraft between two locations to make the journey easy by allowing necessary layover time.

Time for layover: 6 hours (say).

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Data taken from Vistara Airlines

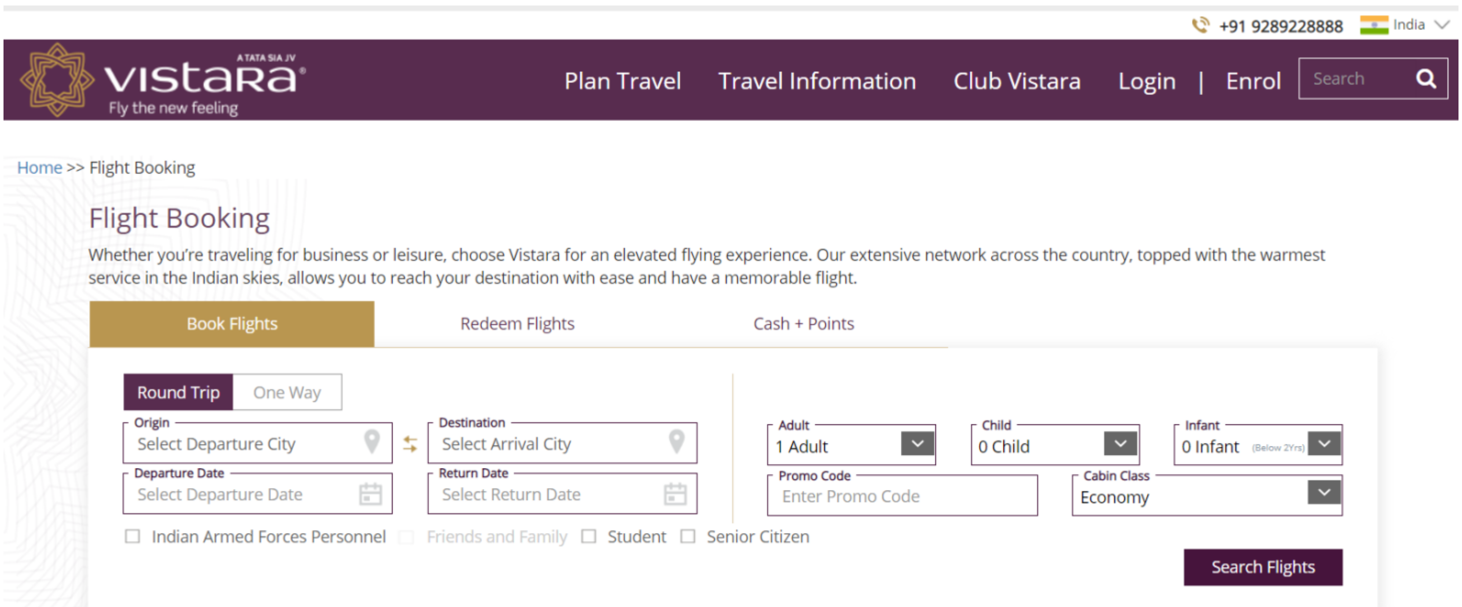

Fig. 4: Vistara Airline Website

```
In [7]: runfile('E:/Dissertation_2nd_sem/db.py', wdir='E:/Dissertation_2nd_sem')
Flight_No.    Delhi_Departure_Time    Mumbai_Arr_Time    Flight_No._Return    Mumbai_Dep_Time    Delhi_Arr_Time
UK975         05:45:00                07:55:00              UK994             10:20:00              12:40:00
UK943         07:30:00                09:40:00              UK960             11:55:00              14:05:00
UK963         08:50:00                11:15:00              UK952             12:25:00              14:50:00
UK927         09:30:00                11:35:00              UK944             14:40:00              16:55:00
UK995         10:20:00                12:35:00              UK902             15:45:00              18:05:00
UK945         11:40:00                13:55:00              UK910             17:35:00              19:45:00
UK993         12:50:00                15:00:00              UK996             18:30:00              20:40:00
UK951         14:20:00                16:30:00              UK940             19:45:00              21:55:00
UK933         15:30:00                17:35:00              UK988             20:55:00              23:00:00
UK941         16:35:00                19:05:00              UK950             21:10:00              23:55:00
```

Fig. 5: Data set taken from Vistara Airlines

There are two scenarios that could occur:

1) when the crew is based in Delhi,

2) when the crew is situated in Mumbai.

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The following are the stopover times for various service line connections if all crew members are stationed at Delhi:

	UK994	UK960	UK952	UK944	UK902	UK910	UK996	UK940	UK988	UK950
UK975	26.42	28.00	28.50	6.75	7.83	9.67	10.58	11.83	13.00	13.25
UK943	24.67	26.25	26.75	29.00	6.08	7.92	8.83	10.08	11.25	11.50
UK963	23.08	24.67	25.17	27.42	28.50	6.33	7.25	8.50	9.67	9.92
UK927	22.75	24.33	24.83	27.08	28.17	6.00	6.92	8.17	9.33	9.58
UK995	21.75	23.33	23.83	26.08	27.17	29.00	29.92	7.17	8.33	8.58
UK945	20.42	22.00	22.50	24.75	25.83	27.67	28.58	29.83	7.00	7.25
UK993	19.33	20.92	21.42	23.67	24.75	26.58	27.50	28.75	29.92	6.17
UK951	17.83	19.42	19.92	22.17	23.25	25.08	26.00	27.25	28.42	28.67
UK933	16.75	18.33	18.83	21.08	22.17	24.00	24.92	26.17	27.33	27.58
UK941	15.25	16.83	17.33	19.58	20.67	22.50	23.42	24.67	25.83	26.08

Fig. 6: Crew based in Delhi

Similarly, layover time is computed for crew members stationed in Mumbai (so that they depart from and return to Mumbai with a minimum stop in Delhi):

	UK994	UK960	UK952	UK944	UK902	UK910	UK996	UK940	UK988	UK950
UK975	17.08	15.67	14.92	12.83	11.67	10.00	9.08	7.83	6.75	5.83
UK943	18.83	17.42	16.67	14.58	13.42	11.75	10.83	9.58	8.50	7.58
UK963	20.17	18.75	18.00	15.92	14.75	13.08	12.17	10.92	9.83	8.92
UK927	20.83	19.42	18.67	16.58	15.42	13.75	12.83	11.58	10.50	9.58
UK995	21.67	20.25	19.50	17.42	16.25	14.58	13.67	12.42	11.33	10.42
UK945	23.00	21.58	20.83	18.75	17.58	15.92	15.00	13.75	12.67	11.75
UK993	24.17	22.75	22.00	19.92	18.75	17.08	16.17	14.92	13.83	12.92
UK951	25.67	24.25	23.50	21.42	20.25	18.58	17.67	16.42	15.33	14.42
UK933	26.83	25.42	24.67	22.58	21.42	19.75	18.83	17.58	16.50	15.58
UK941	27.92	26.50	25.75	23.67	22.50	20.83	19.92	18.67	17.58	16.67

Fig. 7: Crew based on Mumbai

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Select the shortest value between the two layover times for the various route connections, as long as the value is greater than six hours (the minimum acceptable layover time), if it is not- add 24 hours to it. :

Final Table

	UK994	UK960	UK952	UK944	UK902	UK910	UK996	UK940	UK988	UK950
UK975	17.08	15.67	14.92	6.75	7.83	9.67	9.08	7.83	6.75	5.83
UK943	18.83	17.42	16.67	14.58	6.08	7.92	8.83	9.58	8.50	7.58
UK963	20.17	18.75	18.00	15.92	14.75	6.33	7.25	8.50	9.67	8.92
UK927	20.83	19.42	18.67	16.58	15.42	6.00	6.92	8.17	9.33	9.58
UK995	21.67	20.25	19.50	17.42	16.25	14.58	13.67	7.17	8.33	8.58
UK945	20.42	21.58	20.83	18.75	17.58	15.92	15.00	13.75	7.00	7.25
UK993	19.33	20.92	21.42	19.92	18.75	17.08	16.17	14.92	13.83	6.17
UK951	17.83	19.42	19.92	21.42	20.25	18.58	17.67	16.42	15.33	14.42
UK933	16.75	18.33	18.83	21.08	21.42	19.75	18.83	17.58	16.50	15.58
UK941	15.25	16.83	17.33	19.58	20.67	20.83	19.92	18.67	17.58	16.67

Fig. 8: Combined Matrix

Result after applying Hungarian Method (Munkres)

```
(0, 3) -> 6.75
(1, 4) -> 6.08
(2, 5) -> 6.33
(3, 6) -> 6.92
(4, 7) -> 7.17
(5, 8) -> 7.0
(6, 9) -> 6.17
(7, 0) -> 17.83
(8, 1) -> 18.33
(9, 2) -> 17.33
total layover time: 99.91
```

Fig. 9: Result after applying Hungarian Method (Munkres)

Conclusion

The Hungarian method, a powerful technique in operations research, offers several benefits when applied to crew scheduling in airlines. Here are some of the advantages:

1. Efficiency: The Hungarian method efficiently solves the assignment problem, which is crucial in crew scheduling where numerous flights need to be assigned to available crew members. Its time complexity of $O(n^3)$ allows for practical implementation even in large-scale scheduling scenarios, resulting in faster computation times compared to exhaustive search or other combinatorial optimization approaches.

2. Optimality: The Hungarian method provides an assured optimal solution for the assignment problem. When applied to crew scheduling, this means generating crew assignments that minimize costs, maximize crew utilization, or achieve specific objectives. By considering factors such as crew availability, qualifications, and preferences, the method ensures that crew members are assigned to flights in the most optimal way possible.

3. Constraint Handling: Crew scheduling in airlines involves multiple constraints, including crew legality (working hour limits, rest requirements, skill-based regulations), crew preferences, flight connections, and other operational requirements. The Hungarian method can accommodate these constraints within the assignment problem framework. By formulating the problem appropriately and incorporating relevant constraints, the method produces crew schedules that satisfy legal regulations, crew preferences, and operational constraints.

4. Flexibility: The Hungarian method is flexible and adaptable to different crew scheduling scenarios. It can handle variations in crew availability, flight schedules, and regulatory requirements. The method allows for modifications to the assignment matrix, enabling adjustments to crew qualifications, preferences, or other factors. This flexibility makes it suitable for both routine crew scheduling and managing unforeseen disruptions or changes in operational conditions.

5. Integration with Other Techniques: The Hungarian method can be integrated with other operations research techniques to enhance crew scheduling optimization. For example, it can be combined with stochastic programming to consider uncertainties in crew availability or flight delays. It can also be used in conjunction with crew pairing algorithms to improve crew productivity and minimize deadhead travel time.

6. Practical Implementation: The Hungarian method's mathematical formulation and algorithmic approach make it practical for implementation in crew scheduling systems. Its systematic step-by-step algorithm allows for efficient computation and can be integrated into software or decision support tools used by airlines. This facilitates the integration of the method into existing crew scheduling processes, leading to more effective and automated scheduling solutions.

In summary, the Hungarian method offers numerous benefits when applied to crew scheduling in airlines. Its efficiency, optimality, ability to handle constraints, flexibility, integration capabilities, and practical implementation make it a valuable tool for generating optimal crew schedules, improving crew utilization, and ensuring compliance with regulatory requirements. By leveraging the advantages of the Hungarian method, airlines can enhance their crew scheduling processes, resulting in improved operational efficiency and crew satisfaction.

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Appendix

```
import sqlite3
#import numpy as np
from itertools import islice
#from datetime import datetime
import pandas as pd
#import munkres
sql_connect = sqlite3.connect('airline.db')
cursor = sql_connect.cursor()
#query = "SELECT * FROM airline;"
#results = cursor.execute(query).fetchall()
#cursor.execute("""
#                CREATE TABLE `Airport` (
#     `Code` CHAR(3) NOT NULL DEFAULT '',
#     `City` VARCHAR(50) DEFAULT NULL,
#     `State` CHAR(2) DEFAULT NULL,
#     PRIMARY KEY (`Code`)
#)
#                """)
#airport_details=[('LOG', 'Boston', 'MA'),('ORD', 'Chicago', 'IL'),('MDW', 'Chicago', 'IL'),('JFK',
#cursor.executemany("INSERT INTO Airport VALUES (?,?,?)",airport_details)

#cursor.execute("select * from Airport")
#print(cursor.fetchall())

#cursor.execute("""
#              CREATE TABLE `Details` (
#     `Flight_No.` VARCHAR(5) NOT NULL DEFAULT '',
#     `Delhi_Departure_Time` TIME,
#     `Mumbai_Arrival_Time` TIME,
#     `Flight_No._Return` VARCHAR(5) NOT NULL DEFAULT '',
#     `Mumbai_Departure_Time` TIME,
#     `Delhi_Arrival_Time` TIME
#)
 #               """)
#flight_details=[('UK975','05:45:00','07:55:00','UK994','10:20:00','12:40:00'),
#                 ('UK943','07:30:00','09:40:00','UK960','11:55:00','14:05:00'),
#                 ('UK963','08:50:00','11:15:00','UK952','12:25:00','14:50:00'),
#                 ('UK927','09:30:00','11:35:00','UK944','14:40:00','16:55:00'),
#                 ('UK995','10:20:00','12:35:00','UK902','15:45:00','18:05:00'),
#                 ('UK945','11:40:00','13:55:00','UK910','17:35:00','19:45:00'),
#                 ('UK993','12:50:00','15:00:00','UK996','18:30:00','20:40:00'),
#                 ('UK951','14:20:00','16:30:00','UK940','19:45:00','21:55:00'),
#                 ('UK933','15:30:00','17:35:00','UK988','20:55:00','23:00:00'),
#                 ('UK941','16:35:00','19:05:00','UK950','21:10:00','23:55:00')]
#cursor.executemany("INSERT INTO Details VALUES (?,?,?,?,?,?)",flight_details)
```

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```
cursor.execute("select * from Details")
#print(cursor.fetchall())
flights=cursor.fetchall()
print("Flight_No."+"\t\tDelhi_Departure_Time"+"\tMumbai_Arr_Time"+"\t\tFlight_No._Return"+"\t\tMumbai_Dep
for flight in flights:
    print(flight[0]+"\t\t\t"+flight[1]+"\t\t\t\t"+flight[2]+"\t\t\t\t"+flight[3]+"\t\t\t\t"+flight[4]+"\t
#print(flights[0][1])
#matrix1=[[flights[0][4]-flights[0][2],flights[1][4]-flights[0][2]]]
#print(flights[1][3])
print("\nCrew based in Delhi")
list1=[]
for i in range (0,10):
            value1=pd.Timestamp(flights[i][2])
            for j in range(0,10):
                value2=pd.Timestamp(flights[j][4])
                value=value2-value1
                td=pd.Timedelta(value)
                minutes = td.total_seconds()/60
                hours = minutes/60
                rounded_hour=round(hours,2)
                if rounded_hour<6:
                    rounded_hour=rounded_hour+24
                list1.append(rounded_hour)
#print(list1)
#print(np.array_split(list1,10))
length_to_split=[10,10,10,10,10,10,10,10,10,10]
input_list=iter(list1)
output=[list(islice(input_list,elem))
        for elem in length_to_split]
#print(output)
#print(*output, sep='\n')
headers=["UK994","UK960","UK952","UK944","UK902","UK910","UK996","UK940","UK988","UK950"]
row_wise_headers=["UK975","UK943","UK963","UK927","UK995","UK945","UK993","UK951","UK933","UK941"]
print(pd.DataFrame(output,row_wise_headers,headers))
```

```
print("\nCrew based in Mumbai")
list2=[]
for i in range (0,10):
            value3=pd.Timestamp(flights[i][1])
            for j in range(0,10):
                value4=pd.Timestamp(flights[j][5])
                value=value3-value4
                td=pd.Timedelta(value)
                minutes = td.total_seconds()/60
                hours = minutes/60
                rounded_hour=round(hours,2)
                if rounded_hour<6:
                    rounded_hour=rounded_hour+24
                list2.append(rounded_hour)
```

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```
length_to_split2=[10,10,10,10,10,10,10,10,10,10]
input_list2=iter(list2)
output2=[list(islice(input_list2,elem))
        for elem in length_to_split2]
headers=["UK994","UK960","UK952","UK944","UK902","UK910","UK996","UK940","UK988","UK950"]
row_wise_headers=["UK975","UK943","UK963","UK927","UK995","UK945","UK993","UK951","UK933","UK941"]
print(pd.DataFrame(output2,row_wise_headers,headers))
#print(output2)
print("\nFinal Table")
combined_minimum=[min([x,y]) for x,y in zip(list1,list2)]
#print(combined_minimum)
length_to_split3=[10,10,10,10,10,10,10,10,10,10]
input_list3=iter(combined_minimum)
respective_minimum_value=[list(islice(input_list3,elem))
        for elem in length_to_split3]
headers=["UK994","UK960","UK952","UK944","UK902","UK910","UK996","UK940","UK988","UK950"]
row_wise_headers=["UK975","UK943","UK963","UK927","UK995","UK945","UK993","UK951","UK933","UK941"]
print(pd.DataFrame(respective_minimum_value,row_wise_headers,headers))

sql_connect.commit()
sql_connect.close()
```

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