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DEVELOPMENT OF A MATHEMATICAL MODEL FOR MANAGING SCHEDULE DELAYS IN AIR TRAFFIC OPERATIONS

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The object of this research is delay in air traffic operations. The problem in this research that must be solved is how to reduce the impact of frequent delays which cause time efficiency but cause increased operational costs and make customers dissatisfied with air traffic services and then there is time complexity which is difficult to overcome. The interpretation of this research is to analyze existing problems and then apply mathematical methods so that it is possible to develop a model that is able to dynamically optimize flight rescheduling which can be beneficial for customers in reducing waiting times. This model will consider many important variables in managing delay schedules including real-time weather conditions, aircraft availability, airport capacity so that the results of this model show the ability to reduce the frequency and duration of delays which can increase customer satisfaction. This application shows that the model developed has main characteristics such as flexibility in adjusting schedules in terms of delays and accuracy in predicting potential delays so that the problems analyzed and researched can be resolved effectively and efficiently. This model can predict schedule delays with an accuracy level of 90 % according to predetermined input variables. Then there are quantitative benefits in the form of reducing operational costs for delays, increasing prediction accuracy and optimizing flight schedules. Qualitatively there are benefits in customer satisfaction and faster and more effective decision making. The scope of this research includes managing flight schedules at airports and international hubs. Implementation of this model is important to ensure high operational efficiency and minimize the impact of delays in various operational conditions

Keywords: air traffic management, mathematical models, schedule delay management, optimization, operational efficiency, aviation industry

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1. Introduction

Air traffic is a vital aspect of global transportation that enables the mobility of people and goods from one place to another quickly and efficiently [1]. In recent years, economic development and technological developments have led to a significant increase in the number of flights, both on a national and international scale [2, 3]. However, this increase has also been accompanied by major challenges in air traffic management, especially related to flight scheduling and delays. Schedule delays are a frequent problem in the aviation industry and can have a detrimental impact on both airlines, airport operators and passengers. The impacts include additional costs for airlines, inconvenience for passengers, and disruption to airport operational efficiency [4, 5]. In managing schedule delays, it is important to have an appropriate mathematical model that can help predict, analyze and optimize flight schedule settings [6, 7].

The increase in the number of flights that has occurred in recent years has also given rise to new challenges in managing schedule delays. The increasing number of flights increases the complexity of the air traffic system, increasing the possibility of schedule delays due to traffic congestion, aircraft delays and other problems. This shows the need for the development of more sophisticated and adaptive mathematical models to overcome these new challenges [8, 9]. Additionally, schedule delays can also have far-reaching and complex impacts on various aspects of the aviation industry, including economics, safety and the environment. Repeated schedule delays can cause significant financial losses for airlines, as well as disrupt travel schedules and harm the passenger experience [10, 11]. On the other hand, schedule delays can also increase the risk of accidents and incidents in the air, which can impact overall flight safety. Apart from that, schedule delays can also cause increased greenhouse gas emissions and air pollution due to wasted fuel by planes that are late taking off or landing [12]. Taking into account the complexity and far-reaching impact of schedule delays in air traffic operations, the development of effective and reliable mathematical models becomes increasingly important. Sophisticated and adaptive mathematical models can help decision makers in the aviation industry to identify factors causing schedule delays, plan flight schedules more efficiently, and optimize the use of available resources.

Mathematical models are powerful tools for modeling the complexity of air traffic systems and can provide valuable insights in decision making. Through the use of sophisticated mathematical models, decision makers can plan flight schedules more efficiently, anticipate possible delays, and optimize the use of available resources [13]. Several factors that need to be considered in developing mathematical models to manage schedule delays in air traffic operations include weather variability, airport capacity, airway availability, aircraft availability, and passenger needs and preferences [14, 15]. In addition, changes in aviation regulations and government policies can also affect flight schedule settings and require adjustments in the mathematical models used. Thus, research on the development of mathematical models for managing schedule delays in air traffic operations has significant relevance in the context of the current aviation industry. By using a careful and innovative approach in developing mathematical models, it is hoped that effective solutions can be found to overcome the challenges faced in flight schedule delay management, thereby increasing operational efficiency and service quality in the aviation industry.

By using a careful and innovative approach in developing mathematical models, it is hoped that effective solutions can be found to overcome the challenges faced in flight schedule delay management, thereby increasing operational efficiency and service quality in the aviation industry. Therefore, studies devoted to air traffic delay management have very significant relevance in managing air traffic schedule delays by developing mathematical models so that they can have a significant impact in the world of aviation.

2. Literature review and problem statement

Research [16] presents a model for slot allocation in air traffic flow management that will specifically reduce delays so that it will improve data integration for airport slots. Research will show that slot allocation at airports can reduce the impact of delays on flight traffic. However, there are problems that have not been resolved, such as managing a long time in allocating slots, so this problem can be solved by developing a mathematical model using the variables needed in air traffic.

Research [17] proposed a heuristic approach to develop a more environmentally friendly Extended-Arrival Manager (E-AM) in air traffic control. This approach utilizes dynamic speed control supported by a machine learning-based delay prediction model to optimize the flow of aircraft arrivals in real-time. This research shows that implementing this method can reduce carbon emissions and increase fuel efficiency by minimizing delays that occur. However, there are challenges regarding the accuracy of delay prediction models and the integration of dynamic speed control systems with existing air traffic control infrastructure. To overcome these challenges, this research recommends further development with implementation.

Research [18] takes an approach in analyzing factors that can be part of influencing international flight delays and their impact on airline operations and management. This research will carry out analyzes such as weather and operational conditions. The results obtained from this research are a model for processing delays but it has shortcomings in operational management which have an impact on compensation costs. So that the development of mathematical models can solve these problems in carrying out flight management.

Research [15] presents research results using a queue-based integer programming approach to control the time between aircraft arrivals to reduce arrival traffic delays. This research shows that the queuing approach is able to optimize the time between aircraft arrivals so that it can reduce delays significantly. However, there are unresolved problems related to the complexity of the integer programs used, especially when faced with very dynamic traffic conditions. One way to overcome this problem is to develop a more adaptive and efficient algorithm for managing arrival queues. This approach has been widely used, but has never been widely applied to very dynamic air traffic scenarios, so it is recommended to carry out further studies on the application of more flexible algorithms in this context.

Research [11] presents research results using an adaptive framework for optimization and prediction in air traffic management systems with machine learning. This research shows that machine learning can be used to optimize and predict the performance of (sub-)systems in air traffic management. However, there are unresolved issues related to the complexity of the machine learning models used, especially when faced with scenarios that require rapid adaptation to changing operational conditions. One way to overcome this problem is to integrate more adaptive machine learning models with flexible optimization algorithms. This approach has been widely used, but has never been widely applied to large-scale air traffic management systems, so it is recommended to conduct further studies on the application of this adaptive framework in more complex and dynamic scenarios.

Research [19] presents research results using a deep learning approach in air traffic management (ATM). This research shows that deep learning can be applied to various aspects of ATM, including traffic prediction, route management, and anomaly detection. However, there are unresolved issues related to the complexity of deep learning architectures, especially in terms of interpretability and the need for large data for model training. One way to overcome this problem is to develop interpretability techniques in developing mathematical models for efficient learning methods. This approach has been widely used, but has never been widely applied in large-scale ATM scenarios, so it is recommended to carry out further studies on the development of measurable mathematical models to obtain maximum results.

Research [20] presents research results using a variation of the ATC (Air Traffic Controller) work shift scheduling problem to handle incidents at the airport control center. This research shows that these scheduling variations can help improve incident response by ensuring more optimal allocation of human resources. However, there are unresolved problems related to the complexity of scheduling adapted to emergency situations, especially when faced with limited numbers of personnel and work regulations. One way to overcome this problem is to develop a mathematical model that can manage scheduling. This approach has been widely used, but has never been widely applied in complex incident scenarios, so it is recommended to carry out further studies on the application of developing effective and efficient mathematical models.

3. The aim and the objectives of the study

The aim of this study is to develop an effective mathematical model in managing schedule delays in air traffic operations. This model is designed to be a reliable tool in analyzing, predicting and managing schedule delays by considering various factors that influence the air traffic system.

To achieve this aim, the following objectives are accomplished:

– determine the key variables that influence schedule delays in air traffic operations;

– evaluate models for delaying flight traffic.

4. Materials and methods

The object of this study is delay in air traffic operations. In flight flow management, it can be managed well by utilizing the development of a mathematical model which will consider many important variables in managing delayed schedules including real-time weather conditions, aircraft availability, airport capacity so that the results of this model show the ability to reduce the frequency and duration of delays which can increase customer satisfaction. This research has a hypothesis regarding delays in thinning air traffic. In this context there will be a goal of improving existing mathematical models to increase the ability to reduce the frequency and duration of delays which can increase customer satisfaction. The approach that will be used in implementing an optimization-based mathematical model will consider factors such as weather conditions, traffic density, passenger delays, coordination between airports, and aircraft delays. By using techniques and mathematical formulas such as optimization, simulation and algorithms, it is hoped that models can be developed that can help find optimal solutions to increase efficiency in managing flight delays. This research uses laptop hardware and uses software in the form of Anaconda, Microsoft Visio and Photoshop. In research conducted by [18] there are shortcomings such as delays in making predictions due to the data having to be of good quality and the complexity of the heuristic approach which requires operational adjustments to aircraft speed which will then influence inconsistent response times in predicting delays or flight delays. However, by implementing the development of mathematical models, response times and complexity in adjusting variables or parameters used in predicting air traffic flight scheduling delays can be reduced. This research will begin by designing the architecture as shown in Fig. 1.

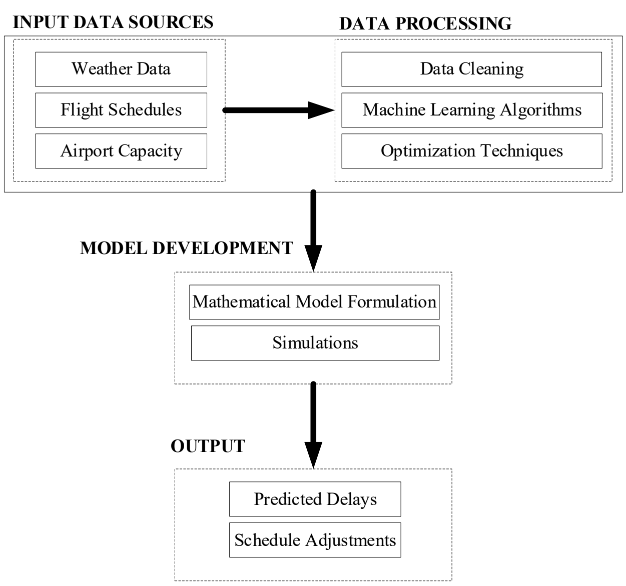

Fig. 1. Scheduling management architecture

In Fig. 1, there will be an architecture for scheduling management which consists of stages such as data input, data processing, model development and results. Each stage will consist of processes that can help in applying the development of mathematical models in the context of organizing and managing scheduling delays in air traffic. At the data input stage, there will be several parameters that will be used, including weather, flight schedules and airport capacity, then data processing will be carried out to clean the data, determine optimization techniques and determine the algorithm used. After the data input and data processing stages have been carried out, the next step will be to apply mathematical models and simulations to control the scheduling of air traffic delays. The mathematical model formulation will use the objective function and constraint function which will be contained in the following equation:

$$z = \sum_i \sum_j C_{ij} . d_i . \tag{1}$$

Equation (1) will minimize the total costs associated with schedule delays with parameters C_{ij} costs or penalties associated with aircraft i being late at airport j. there will be a decision variable for the actual delay of aircraft i which will calculate the difference between the actual arrival time and the scheduled arrival time. Then there will be equation (2)–(5) related to the constraint function:

$$\sum_i x_{ij} \le S_j \forall j; \tag{2}$$

$$t_i + A_{ij} \le t_j \forall i, j; \tag{3}$$

$$t_i \ge t_{i-1} + R_i \forall i; \tag{4}$$

$$d_i = t_{i,actual} - t_i . \tag{5}$$

In equation (2), there will be an airport capacity constraint function which aims to ensure that the number of aircraft at airport j does not exceed capacity. In equation (3) the travel time constraint function looks at the arrival time of plane i at airport j. in equation (4) the cucumber time constraint which will look at the take-off time of aircraft i must consider the time required before taking off again. Then equation (5) looks at the time difference between the real time arrival time and the scheduled arrival time.

5. Results mathematical model for managing schedule delays in air traffic operations

5. 1. Determination the key variables that influence schedule delays in air traffic operations

In developing this mathematical model, it is possible to manage delays in air traffic operation schedules, considering several variables that will influence the timeliness of aircraft arrival. This model will depict the plane arrival schedule with symbols i then for symbols A_i will present the actual arrival time of the plane to i. then the difference between actual arrival time and arrival according to schedule is symbolized by $D_i = A_i - S_i$ which will explain that value $D_i > 0$ will show that the plane is experiencing delays and needs to be postponed and managed by temporary delay scheduling management $D_i < 0$ will describe the plane arriving on schedule. This model also takes into account external conditions such as weather conditions $W(t)$ at time t, which can affect the smooth running of flight operations. Apart from that, airport capacity $C(t)$ at time t and the number of planes arriving $N(t)$ is also an important variable that plays a role in determining the level of delay. The available runway capacity $R(t)$ at time t is also a key factor in this model, because limited runway capacity can cause delays in aircraft landing. Through the integration of these variables, this mathematical model can provide a more comprehensive and predictive picture related to managing delays in air traffic operations schedules. The following is the development of a mathematical model according to equation (1)–(5):

$$D_i = f\left(W(t), C(t), N(t), R(t)\right) + \epsilon_i . \quad (6)$$

In equation (6), there are the factors that influence delays so that they can be managed and then developed with formulations:

$$\sum_{i=1} D_i; \quad (7)$$

$$N(t) \leq C(t), R(t) \geq N(t), \forall t;$$

$$w(t) \leq w_{\max}. \quad (8)$$

In equation (7), it is possible to carry out a technique to minimize the total delay of all aircraft in a certain time period so that good management can be carried out which then produces equation (8) which will take into account the safe limit of weather conditions with the symbol $W_{\max}$.

5. 2. Flight delay model testing

After obtaining the algorithm from the modeling above, proceed with data testing. Testing data from the airline scheduling optimization algorithm using Bahara R. The following is the program code data from testing the airline scheduling optimization algorithm:

```
set.seed(123) # Set seed for reproducibility
planes <- data.frame(
  id = 1:10,
  capacity = sample(10:20, 10, replace = TRUE),
  stringsAsFactors = FALSE
)
flights <- data.frame(
  id = 1:5,
  max_time = sample(200:300, 5, replace = TRUE),
  max_distance = sample(500:600, 5, replace = TRUE),
  turnaround_time = sample(10:20, 5, replace = TRUE),
  turnaround_distance = sample(50:100, 5, replace = TRUE),
  stringsAsFactors = FALSE
)

airports <- data.frame(
  id = 1:12,
  capacity = sample(50:100, 12, replace = TRUE),
  stringsAsFactors = FALSE
).
```

The code above is the code for inputting airline data, flight data and airport data. The number of airlines is 10, flight data is 5 and airport data is 12.

Below are flight simulation data and flight charts containing numbers, codes, maximum time, maximum distance, turnaround time dan turnaround distance. The following flight data is in Table 1.

The flight data contained in Table 1 will produce a flight data graph which will be shown in Fig. 2.

Table 1

Flight data

Number	Code	Maximum time	Maximum distance	Turn-around time	Turn-around distance
1	1	217	595	10	81
2	2	254	554	20	67
3	3	231	504	12	79
4	4	200	536	18	64
5	5	211	553	19	7

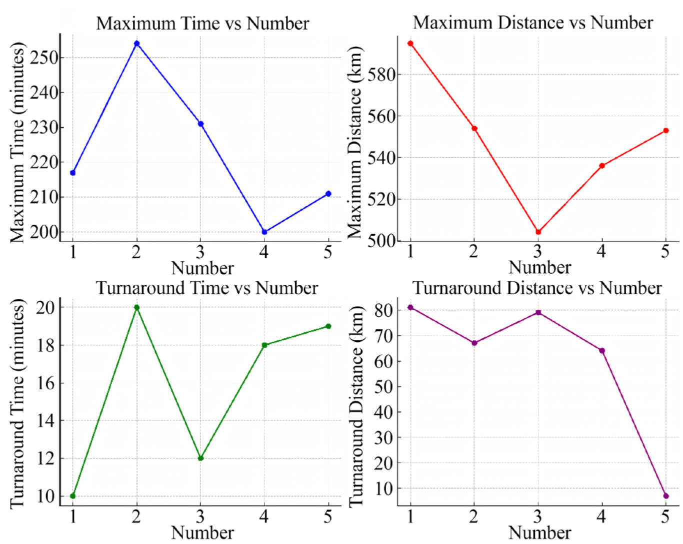

Fig. 2. Flight data

The results of the optimization from the initial data reveal that the maximum time and distance for each item have been improved, leading to better values than those in the original dataset. For example, item 1 now has a time maximum of 289 and a distance maximum of 591, which is lower than the time maximum of 217 and distance maximum of 595 in the initial data. The turnaround time and turnaround distance for each item have also been optimized to achieve lower values than the initial data. This suggests that this test may try to minimize waiting times and waiting distances in transit. The maximum time and maximum distance values for each item tend to vary. Item 1 has a higher time maximum value than items 3 and 5, but has a lower distance maximum value than items 2 and 4. This shows that the time maximum and distance maximum values are not always directly correlated. In summary, the available data indicates that the maximum time and distance values for each item have been optimized to achieve improved results compared to the initial figures. Then, from this data, mathematical model training will be carried out which will produce a model that can be used to manage delays in air traffic. The following are the results of model training in Fig. 2.

Fig. 3 will explain the training in developing mathematical models, which in Fig. 3 produces the best air traffic delayed training so that this mathematical development model can be used effectively and displays accuracy during the training process with decreasing and increasing plots, produces the best accuracy with a predetermined number of epochs and displays the target accuracy content expected to reach 0.91.

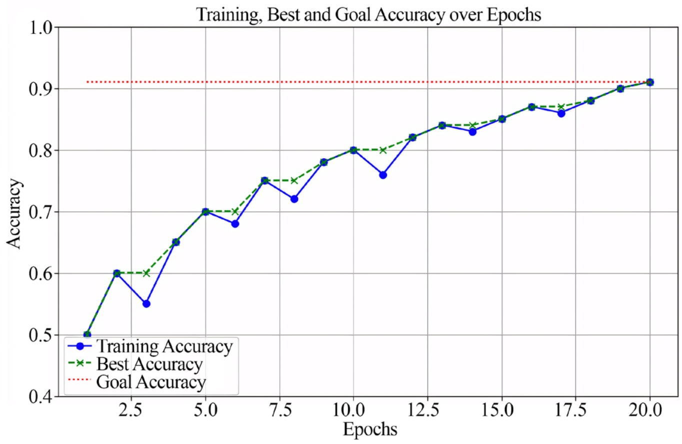

Fig. 3. Training results

data distribution is also very necessary. One of the main weaknesses is the sensitivity of the model to changes in input data, which can result in variations in results. In addition, the application of these mathematical models requires a complex approach, which may be difficult to apply in real situations. To overcome these challenges, a more in-depth analysis of the input data that is most relevant to the applied mathematical model is needed. This includes weather variables, aircraft availability at the airport, and flight schedules. Further research could focus on increasing model complexity with the integration of machine learning technology, which could provide deeper insights and improve model performance in the face of changing air traffic conditions. In addition, by considering humanitarian aspects such as decision-making processes and air traffic control in mathematical models, the resulting solutions will be more effective.

6. Discussion of managing flight scheduling delays

This research produces a mathematical model which is expected to provide solutions in managing air traffic. The resulting model include mathematical formulas to determine functions that can reduce costs represented by equation (1), formulate weather in equations (2), (3), determine mathematical traffic density in equation (4) and aircraft delays (5). This research shows that the use of optimized mathematical models has resulted in effective algorithms, as described in (1)–(8).

This is different from research [19] which results in applying a deep learning model in carrying out air traffic management but there are shortcomings in terms of implementing the deep learning architecture which experiences complexity in the interpretability process when processing big data. The proposed solution can solve this problem by developing. The mathematical model in (6)–(8) will apply the development of a mathematical model to a deep learning architecture that will be able to process large-scale data in air traffic scheduling management processing.

This research produces the data in Fig. 1 which is data in carrying out air traffic delay management which will then produce a graph from this data which is in Fig. 2 with data on distance and time in flight management which is then carried out training which produces the sequence of results in Fig. 3 displays the accuracy during the training process with a decreasing and increasing plot, producing the best accuracy with a predetermined number of epochs and displays the expected target of the accuracy content which reaches 0.91.

In this research there are limitations such as the need for scheduling data that can be received in real time which includes airport capacity, weather and schedule delays so that the model that has been developed can complete the process in real time. In its application, the mathematical model applied will depend on large data and data that does not change within a predetermined time, therefore real-time

7. Conclusions

1. This research succeeded in identifying a number of variables that influence the management of delayed air traffic, including variables such as weather conditions, air traffic density, duration of aircraft completion and infrastructure availability. In this context, it is also proven by equations that by integrating these variables, this mathematical model can provide a more comprehensive and predictive picture regarding the maintenance of delayed air traffic operation schedules.

2. The results of the evaluation show that the model has an accuracy of 0.91 in predicting air traffic delays with a predetermined number of epochs.

Conflict of interest

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

Financing

The study was performed without financial support.

Data availability

Manuscript has no associated data.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

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